PB-219 074

Hydrocarbon Pollutant Systems Study

Vol. 2 Appendices

MSA Research Corp.

prepared for
Environmental Protection Agency

JANUARY 1973

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MSAR 73-14
AC-860

PB 219 074

FINAL REPORT

to

Environmental Protection Agency
Office of Air Programs
Research Triangle Park, North Carolina 27711

on

HYDROCARBON POLLUTANT SYSTEMS STUDY

VOLUME II - APPENDICES

25 January 1973

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Office of Air Programs
Research Triangle Park, N. C. 27711

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Final

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16. Abstracts

A study was conducted to develop a problem-solving R & D program for the control of hydrocarbon air pollutants from major stationary sources. This volume of the report contains nine appendices for the study. The appendices present information as follows. Calculations, quotes and correspondence for gasoline storage tanks, incineration, and adsorption. Basic information and tables are presented for: Incineration-absorption and scrubbing absorption, Incineration-scrubbing systems for hydrocarbon emission control; Particulate-scrubbing systems for hydrocarbon emission control. An analysis of a questionnaire survey, a breakdown of fuel consumption and estimated emissions and review of elementary combustion studies, and a waste combustion emission factors and municipal waste breakdown are presented.

17. Key Words and Document Analysis. 17a. Descriptors

Air pollution
Hydrocarbons
Sources
Systems engineering
Gas storage
Storage tanks
Incinerators
Adsorption
Washing
Absorption

Air pollution control equipment
Particles
Fuel consumption
Waste disposal
Computation

17b. Identifiers/Open-Ended Terms

Stationary sources
Particulates

17c. COSATI Field/Group 13B

18. Availability Statement
Unlimited

19. Security Class (This Report)
UNCLASSIFIED

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UNCLASSIFIED

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The study was directed by Mr. W.J. Cooper, MSA Research Corporation program manager. MSAR personnel contributing significantly to the study were Messrs. W.A. Everson, J.V. Friel, J.S. Greer and C.A. Palladino.

The MSAR study team was ably assisted by four subcontractors: Industrial Health Foundation; Patent Development Associates; Singmaster and Breyer; and University Science Center. Space does not permit individual acknowledgement of all contributing personnel, but the following individuals are recognized for their subcontract direction and contribution: Mr. Harry Bowman, IHF; Dr. B.J. Lerner, PDA; Mr. Stanley Zukowsky, S&B; and Mr. Edwin Snow, USC.

Mr. William R. King, EPA Project Officer provided assistance during all phases of literature collection and review, as well as constructive criticism of the interim results used in compiling this report.

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E	Incineration-Scrubbing Systems for Hydrocarbon Emission Control
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G	Questionnaire Survey Analysis
H	Breakdown of Fuel Consumption and Estimated Emissions and Review of Elementary Combustion Studies
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APPENDIX A

Calculations, Quotes and Correspondence

Gasoline Storage Tanks

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PROCESS CONCEPT FOR CONTROL OF GASOLINE VAPOR EMISSIONS FROM FIXED ROOF STORAGE TANKS VIA CONVERSION WITH INTERNAL FLOATING COVERS OR STORING IN PONTOON FLOATING ROOF TANKS

Fixed roof gasoline storage tanks discharge vapors to the atmosphere by means of tank filling, emptying, and breathing.

Losses can be considerably reduced by eliminating the vapor space within the tanks.

Economic evaluation of pontoon floating roof tanks, fixed roof tanks, and fixed roof tanks with internal floating covers is carried out for nominal tank capacities of 50,000, 100,000, and 150,000 barrels.

SINGMASTER & BREYER
CHEMICAL & METALLURGICAL PROCESS ENGINEERS

COMPUTATION SHEET
J. O. No. PS-228
SHEET No. A-2 OF
DATE 8/2/71
COMP. BY STM C'K'D BY

NAME OF COMPANY MSA RESEARCH CORP.
SUBJECT GASOLINE STORAGE TANK LOSSES - STUDY

BASIS OF EVALUATION

THREE TYPES OF STORAGE TANKS - FIXED ROOF, PONTOON FLOATING ROOF, AND CONVERTED FIXED ROOF WITH INTERNAL FLOATING COVER - STORE GASOLINE WITH A REID VAPOR PRESSURE OF 9.0. AVERAGE ANNUAL OUTAGE IS 50%. NUMBER OF TURNOVERS ARE 10/YEAR

EVALUATE THE ANNUAL FUEL LOSS FROM EACH TYPE OF TANK HAVING THE FOLLOWING NOMINAL CAPACITIES & DIMENSIONS:

50,000 BBL - 90'φ×48'
100,000 BBL - 120'φ×48'
150,000 BBL - 150'φ×48'

I FROM API BULLETIN 2518 - ANNUAL BREATHING LOSS EQUATION FOR FIXED ROOF TANKS; ALSO SHOWN IN API BULLETIN 2523:

$$L_y = \frac{24}{1000}\left(\frac{P}{14.7-P}\right)^{.68} D^{1.73} H^{.51} T^{.5} F_P C$$

WHERE:

L_y = BREATHING LOSS, bbl/yr.
D = TANK DIAMETER, FT.
H = AVG OUTAGE, FT
F_P = PAINT FACTOR = 1 FOR WHITE
C = ADJUSTMENT FACTOR FOR SMALL TANKS
P = VAPOR PRESSURE @ AVG AMBIENT METEOROLOGICAL TEMP. PLUS 5°F
T = AVG DAILY TEMP. DIFFERENCE BETWEEN U.S. WEATHER BUREAU MAX. & MIN TEMPS.

FROM API BULLETINS 2513, 2518, 2523

FILLING & WORKING LOSS EQUATION FOR FIXED ROOF TANKS

$$F = \left(\frac{3PV}{10,000}\right) K_T$$

F = LOSS/TURNOVER
P = VAPOR PRESSURE (SAME AS BREATHING LOSS EQN) - PSIA
V = VOLUME OF LIQUID PUMPED INTO TANK, BBLS
K_T = TURNOVER FACTOR

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SUBJECT GASOLINE STORAGE TANK LOSSES - STUDY

II

FROM API BULLETIN NO 2517 - STANDING STORAGE LOSS EQUATION FOR FLOATING ROOF TANKS:

$$L_Y = K_t D^{1.5} \left(\frac{P}{14.7-P}\right)^{.7} V_w^{.7} k_s k_c k_p$$

WHERE:

L_Y = STANDING STORAGE EVAPORATION LOSS, bbl/yr
K_T = TANK CONSTRUCTION FACTOR
= .045 FOR WELDED CONST. PAN OR PONTOON ROOF, SINGLE OR DOUBLE SEAL
= .110 FOR RIVITED CONST., PONTOON ROOF, DOUBLE SEAL
= .130 FOR RIVITED CONST., PAN ROOF, DOUBLE SEAL
= .140 FOR RIVITED CONST, PAN ROOF, SINGLE SEAL
D = TANK DIAMETER, FT.
P = TRUE VAPOR PRESSURE OF STOCK @ AVG STORAGE TEMP, PSIA
(USE AVG AMBIENT METEOROLOGICAL TEMP + 5°F)
V_W = AVG WIND VELOCITY, MILES/HR
k_s = SEAL FACTOR
= 1.0 FOR TIGHT-FITTING SEALS, 1.33 FOR LOOSE FITTING SEALS
k_c = STORED MATL FACTOR
= 1.0 FOR GASOLINE, .75 FOR CRUDE OIL
k_p = PAINT COLOR FACTOR
= 1.0 FOR LIGHT GRAY OR ALUMINUM,
= .9 FOR WHITE

FROM API BULLETIN NO 2517 - WITHDRAWAL LOSS EQUATION FOR FLOATING ROOF TANKS

$W = \frac{448}{D}$ WHERE W = LOSS, bbls/10^6 bbls THROUGHPUT
D = TANK DIAMETER, FT

III

FROM API BULLETIN NO 2519 - LOSSES FIXED ROOF TANK WITH INTERNAL FLOATING COVERS

LOSS REDUCTION TO BE ANALYZED FROM TEST DATA IN BULLETIN

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SUBJECT GASOLINE STORAGE TANK LOSSES - STUDY

ASSUME. TANKS ARE LOCATED IN PHILADELPHIA, PA, ALL TANKS WELDED CONST, ALL TANKS PAINTED WHITE, TANK SEALS IN GOOD CONDITION

DATA FROM API BULLETIN 2513 IS AS FOLLOWS:

AVG BULK TEMP = 54.9 + 5 = 59.9°F.

P = 4.4 PSIA

$\Delta T = 62.7 - 47.1 = 15.6°F$

$V_W = 10.1$ MPH

FIXED ROOF TANKS

A. (50,000 BBL CAP.)

$$L_Y = .024 \left(\frac{4.4}{14.7-4.4}\right)^{.68} (90)^{1.73} (24)^{.51} (15.6)^{.5} (\cancelto{1}{F_P})(\cancelto{1}{C})$$

$$= .024(.56)(2400)(5.08)(3.95) = 650 \text{ BBL/YR (BREATHING LOSS)}$$

$$F = \left(\frac{3(4.4)(.785)(90)^2(48)}{10,000}\right)(10)(1)\left(\frac{7.48}{42}\right) = 715 \text{ BBL/YR (WORKING LOSS)}$$

ANNUAL LOSS = 1365 BBL/YR

B. (100,000 BBL CAP)

$$L_Y = \frac{(120)^{1.73}}{(90)^{1.73}}(650) = \left(\frac{3900}{2400}\right)(650) = 1070 \text{ BBL/YR (BREATHING LOSS)}$$

$$F = \frac{(120)^2}{(90)^2} \times 715 = 1275 \text{ BBL/YR (WORKING LOSS)}$$

ANNUAL LOSS = 2345 BBL/YR

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SUBJECT GASOLINE STORAGE TANK LOSSES - STUDY

FIXED ROOF TANKS (CON'T)

C. (150,000 BBL CAP)

$$Ly = \frac{(150)^{1.73}}{(90)^{1.73}}(650) = \frac{5900}{2400}(650) = 1580 \text{ BBL/YR (BREATHING LOSS)}$$

$$F = \frac{(150)^2}{(90)^2} \times 715 = 1980 \text{ BBL/YR (WORKING LOSS)}$$
1760

ANNUAL LOSS = 3560 BBL/YR

PONTOON FLOATING ROOF TANKS

A. (50,000 BBL CAP.)

$$Ly = .045\left(\frac{4.4}{10.3}\right)^{.7}(10.1)^{.7}(1)(1)(.9)(D)^{1.5}$$
$$= .045(.55)(5.05)(.9)(D)^{1.5}$$
$$= .1125\, D^{1.5}$$
$$Ly = .1125(90)^{1.5} = 95.5 \text{ Bbl/YR (STANDING STORAGE LOSS)}$$

$$W = \frac{448}{90} = 5 \text{ Bbl}/10^6 \text{ Bbl THROUGHPUT (WITHDRAWAL LOSS)}$$

ANNUAL LOSS = 95.5x2.5 = 98 Bbl/YR

B. (100,000 Bbl CAP.)

$$Ly = .1125(120)^{1.5} = 146 \text{ Bbl/YR (STANDING LOSS)}$$

$$W = \frac{448}{120} = 3.75 \text{ Bbl}/10^6 \text{ Bbl THROUGHPUT (WITHDRAWAL LOSS)}$$

ANNUAL LOSS = $146 + 3.75 \cong 150$ Bbl/YR

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DATE 8/12/71
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SUBJECT GASOLINE STORAGE TANK LOSSES - STUDY

PONTOON FLOATING ROOF TANKS (CONT)

C. (150,000 Bbl Cap)

$Ly = .1125\ (150)^{1.5} = 205$ Bbl/yr (STANDING LOSS)

$W = \frac{448}{150} = 3.0$ Bbl/10^6 Bbl THROUGH PUT (WITHDRAWAL LOSS)

ANNUAL LOSS $= 205 + 4.5 \cong 210$ Bbl/yr

FIXED ROOF TANKS - INTERNAL FLOATING COVERS

API BULLETIN 2519 STATES THAT INTERNAL FLOATING COVERS REDUCE LOSSES BY 47% - 94%. AS A MEANS TO EVALUATE THIS TYPE COVER, A PLOT OF TEST RESULTS WILL BE MADE FROM THE DATA ON PAGE 11 OF THIS BULLETIN. THE MODE VALUE WILL BE USED TO EVALUATE THIS CONTROL METHOD. GASOLINE WAS USED AS THE TEST MATERIAL:

LOSS REDUCTION %:	API TEST NOS	FREQUENCY
45-50%	13,	1
51-55%		-
56-60%		-
61-65%	2,3,14	3
66-70%	4,	1
71-75%		-
76-80%	5,6,7,10	4
81-85%		-
86-90%	1,9,12	3
91-95%	8,11,15	3

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Date 8/12/71
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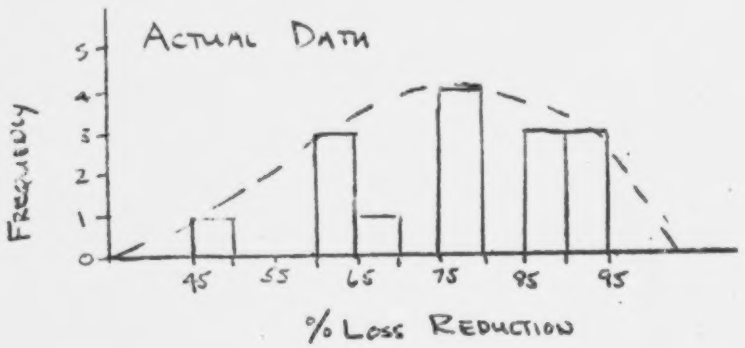
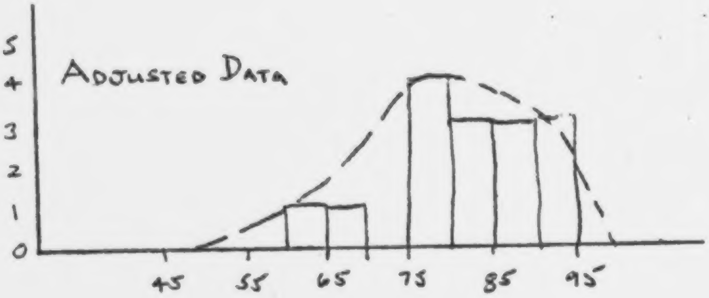
Subject Gasoline Storage Tank Losses - Study

FIXED ROOF TANKS - INTERNAL FLOATING COVERS (CON'T).



If loss reduction below 65% is considered to be due to bad cover seals and the seal factors of API Bulletin 2517 (1.00 for tight fit & 1.33 for loose fit) are used to adjust < 65% values to "tight seal" values, the plot becomes:



Inspection of these distributions indicates a mode of loss reduction at about 80%

Weighted mean values for the actual and adjusted data provide the following respective values

Actual: $\frac{[.5\times1 + .65\times3 + .7\times1 + .8\times4 + .9\times3 + .95\times3]}{15} = .79 \approx 79\%$

Adjusted: $\frac{[.65\times1 + .7\times1 + .8\times4 + .85\times3 + .9\times3 + .95\times3]}{15} = .84 \approx 84\%$

A value of 80% loss reduction will be used (ie reduction from values experienced with fixed roof)

CONSTRUCTION COST ESTIMATE

SINGMASTER & BREYER

CUSTOMER MSA Research Corp.

LOCATION Evans City, Pa

PROJECT PS-228

DESCRIPTION Hydrocarbon Losses-Tank Storage
Cone Roof Tank

PROP. NO.
CONT. NO.
MADE BY
APPROVED

ACCOUNT NUMBER	ITEM & DESCRIPTION	QUANTITY	UNIT	UNIT COSTS			ESTIMATED COST CENTS OMITTED			
				LABOR	SUB CONTR	MAT'L	LABOR	SUB CONTRACTS	MATERIALS	TOTAL
	50,000 BBL Cone Roof Tank - C.S. Const. - 90'ϕ x 48'H - Wt - 187 Tons (Installed Cost - w/o Foundation) Basis; Avg. Value of Budget Quotes									101,500 —
	Excavation: Dike									31,000 —
	Foundation	58	Cu.Yd.							9,300 —
	Electrical Grounding									2,800 —
	Piping	Allow								11,500 —
	Painting									3,000 —
	Land (Existing)								Sub-Total	159,100 —
	Interest on Investment During Const. (3 months @ Prime Rate @ 6%									2,390 —
									Total Capital Cost	161,490 —
									Say	161,000

CODE

(E 153)

DATE ______ REVISION NO. ______ REVISION DATE ______ PAGE NO. A-8

CONSTRUCTION COST ESTIMATE

SINGMASTER & BREYER

CUSTOMER MSA Research Corp.

LOCATION Evans City, Pa

PROJECT PS-228

DESCRIPTION Hydrocarbon Losses - Tank Storage

Cone Roof Tank

PROP. NO.

CONT. NO.

MADE BY

APPROVED

ACCOUNT NUMBER	ITEM & DESCRIPTION	QUANTITY	UNIT	UNIT COSTS			ESTIMATED COST CENTS OMITTED			
				LABOR	SUB CONTR	MAT'L	LABOR	SUB CONTRACTS	MATERIALS	TOTAL
	100,000 BBL Cone Roof Tank - C.S. Const - 120'ϕ × 48'H - Wt. 341 Tons (Installed Cost - w/o Foundation) Basis: Avg. Value of Budget Quotes									171 500
	Excavation: Dike									41 000
	Foundation	77	CY							12 500
	Electrical Grounding									4 500
	Piping									18 900
	Painting									4 800
	Land (Existing)								Sub. Total	253 200
	Interest on Investment During Const. (3 months @ Prime Rate @ 6%)									3 800
									Total Cap Cost	257 000

CODE

(E 153)

DATE REVISION NO. REVISION DATE PAGE NO. A-9

CONSTRUCTION COST ESTIMATE

SINGMASTER & BREYER

CUSTOMER MSA Research Corp.

LOCATION Evans City, Pa.

PROJECT PS-228

DESCRIPTION Hydrocarbon Losses - Tank Storage

Cone Roof Tank

PROP. NO.

CONT. NO.

MADE BY

APPROVED

ACCOUNT NUMBER	ITEM & DESCRIPTION	QUANTITY	UNIT	UNIT COSTS			ESTIMATED COST CENTS OMITTED			
				LABOR	SUB CONTR	MAT'L	LABOR	SUB CONTRACTS	MATERIALS	TOTAL
	150,000 BBL Cone Roof Tank C.S. Const. 150'∅ x 48'H · Wt. 512 Tons (Installed Cost - w/o Foundation) Basis: Avg. Value of Budget Quotes									249 500
	Excavation: Dike									67 200
	Foundation	97	CY							15 500
	Electrical Grounding									6 800
	Piping									27 500
	Painting									7 100
	Land (Existing)									
									Sub Total	373 600
	Interest on Investment During Const. (3 Months @ Prime Rate @ 6%									5 600
									Total	379 200
									Say	379 000

CODE

(E 153)

DATE ______ REVISION NO. ______ REVISION DATE ______ PAGE NO. A-10

CONSTRUCTION COST ESTIMATE

SINGMASTER & BREYER

CUSTOMER MSA Research Corp

LOCATION Evans City, Pa.

PROJECT PS-228

DESCRIPTION Hydrocarbon Losses-Tank Study

Floating Roof Tank - Pontoon Type

PROP. NO.

CONT. NO.

MADE BY

APPROVED

ACCOUNT NUMBER	ITEM & DESCRIPTION	QUANTITY	UNIT	UNIT COSTS			ESTIMATED COST CENTS OMITTED			
				LABOR	SUB CONTR	MAT'L	LABOR	SUB CONTRACTS	MATERIALS	TOTAL
	50,000 BBL Floating Roof Tank C.S. Const. 90'Φ×48'H-Wt. 201 Tons (Installed Cost - w/o Foundations) Basis: Avg. Value of Budget Quotes									115 000
	Excavation: Dike									31 000
	Foundation	158	CY							9 300
	Electrical Grounding									3 000
	Piping									12 700
	Painting									3 280
									Sub-Total	174 280
	Land (Existing)									
	Interest on Investment During Construction (3 Months @ Prime Rate @ 6%)									1 860
									Total Cap Cost	176 140
									Say	176 000

CODE

(E 153)

DATE ______ REVISION NO. ______ REVISION DATE ______ PAGE NO. A-11

CONSTRUCTION COST ESTIMATE

SINGMASTER & BREYER

CUSTOMER MSA Research Corp

LOCATION Evans City, Pa

PROJECT PS-228

DESCRIPTION Hydrocarbon Losses - Tank Study

Floating Roof Tank - Pontoon Type

PROP. NO.

CONT. NO.

MADE BY

APPROVED

ACCOUNT NUMBER	ITEM & DESCRIPTION	QUANTITY	UNIT	UNIT COSTS			ESTIMATED COST CENTS OMITTED			
				LABOR	SUB CONTR	MAT'L	LABOR	SUB CONTRACTS	MATERIALS	TOTAL
	100,000 BBL Floating Roof Tank C.S. Const. 120'Ø × 48'H - Wt. 353 Tons (Installed Cost - w/o Foundation) Basis: Avg Value of Budget Quotes									190 000
	Excavation: Dike									41 000
	Foundation	77	CY							12 500
	Electrical Grounding									5 000
	Piping									20 900
	Painting									5 400
	Land (Existing)								Sub-Total	274 800
	Interest on Investment During Construction (3 Months @ Prime Rate @ 6%)									4 120
									Total Cap Cost	278 920
									Say	279 000

CODE

(E 153)

DATE ______ REVISION NO. ______ REVISION DATE ______ PAGE NO. A-12

CONSTRUCTION COST ESTIMATE

SINGMASTER & BREYER

CUSTOMER MSA Research Corp

LOCATION Evans City, Pa.

PROJECT DS-228

DESCRIPTION Hydrocarbon Loses - Tank Study

Floating Roof Tank - Pontoon Type

PROP. NO.

CONT. NO.

MADE BY

APPROVED

ACCOUNT NUMBER	ITEM & DESCRIPTION	QUANTITY	UNIT	UNIT COSTS			ESTIMATED COST CENTS OMITTED			
				LABOR	SUB CONTR	MAT'L	LABOR	SUB CONTRACTS	MATERIALS	TOTAL
	150,000 BBL Floating Roof Tank C.S. Const. 150'ϕ x 48'H - Wt. 527 Tons (Installed Cost - w/o Foundation) Basis: Avg. Value of Budget Quotes									270 000
	Excavation: Dike									67 200
	Foundation	97	CY							15 500
	Electrical Grounding									7 400
	Piping									29 700
	Painting									7 700
	Land (Existing)								Sub Total	397 500
	Interest on Investment During Construction (3 Months at Prime Rate @ 6%)									5 960
									Total Cap. Cost	403 460
									Say	403 000

CODE

(E 153)

DATE ______ REVISION NO. ______ REVISION DATE ______ PAGE NO. A-13

CONSTRUCTION COST ESTIMATE

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CUSTOMER MSA Research Corp
LOCATION Evans City, Pa
PROJECT PS-228

DESCRIPTION Hydrocarbon Loses - Tank Storage
Float Cover Conversion of Cone Roof Tank

PROP. NO.
CONT. NO.
MADE BY
APPROVED

ACCOUNT NUMBER	ITEM & DESCRIPTION	QUANTITY	UNIT	UNIT COSTS			ESTIMATED COST CENTS OMITTED			
				LABOR	SUB CONTR	MAT'L	LABOR	SUB CONTRACTS	MATERIALS	TOTAL
	Float Cover - 90'ϕ - for 50,000 BBL Cone Roof Tank - Installed Cost Basis: Avg Value of Budget Quotes									33,500 —
	Interest on Investment During Const. (One Month @ Prime Rate @ 6%)									170 —
									Total Cap Conv. Cost	33,670 —
									Say	34,000 —

CODE

(E 153)

DATE ______ REVISION NO. ______ REVISION DATE ______ PAGE NO. A-14

CONSTRUCTION COST ESTIMATE

SINGMASTER & BREYER

CUSTOMER MSA Research Corp

LOCATION Evans City, Pa

PROJECT PS-228

DESCRIPTION Hydrocarbon Losses - Tank Storage
Float Cover Conversion of Cone Roof Tank

PROP. NO.
CONT. NO.
MADE BY
APPROVED

ACCOUNT NUMBER	ITEM & DESCRIPTION	QUANTITY	UNIT	UNIT COSTS			ESTIMATED COST CENTS OMITTED			
				LABOR	SUB CONTR	MAT'L	LABOR	SUB CONTRACTS	MATERIALS	TOTAL
	Float Cover - 120'ϕ - for 100,000 BBL Cone Roof Tank - Installed Cost Basis: Avg Value of Budget Quotes									53,500 -
	Interest on Investment During Const (One Month @ Prime Rate @ 6%)									270 -
									Total Cap Conversion Cost	53,770
									Say	54,000 -

CODE

(E 153)

DATE ______ **REVISION NO.** - **REVISION DATE** ______ **PAGE NO.** A-15

CONSTRUCTION COST ESTIMATE

SINGMASTER & BREYER

CUSTOMER MSA Research Corp

LOCATION Evans City, Pa

PROJECT PS-228

DESCRIPTION Hydrocarbon Losses - Tank Storage

Float Cover Conversion of Cone Roof Tank

PROP. NO. ____

CONT. NO. ____

MADE BY ____

APPROVED ____

ACCOUNT NUMBER	ITEM & DESCRIPTION	QUANTITY	UNIT	UNIT COSTS			ESTIMATED COST CENTS OMITTED			
				LABOR	SUB CONTR	MAT'L	LABOR	SUB CONTRACTS	MATERIALS	TOTAL
	Float Cover - 150'ϕ - For 150,000 BBL Tank - Installed Cost Basis: Avg Value of Budget Quotes									68,000 —
	Interest on Investment During Const. (One Month @ Prime Rate @ 6%)									340 —
									Total Cap Conv. Cost	68,340 —
									Say	68,000 —

CODE

(E 153)

DATE ____ REVISION NO. ____ REVISION DATE ____ PAGE NO. A-16

MANUFACTURING ESTIMATE - STORAGE TANK CONTROL SCHEME

CONTROL PROCESS: GASOLINE STORAGE TANK ~ CONE ROOF 50,000 BBL CAP

PROCESS OPERATING TIME: 3 SHIFTS/DAY 365 DAYS/YR 8750 HR/YR

ITEM	DESCRIPTION	COST	
		$/YR	$/MBBL
RAW MATERIALS	GASOLINE LOSS ~ 57,300 GAL/YR @ .131 / GAL = $7,500.		
UTILITIES:			
COOLING WATER	$.03/10³ GAL.	–	
STEAM	$1.00/10³ LB	–	
NATURAL GAS	$.60/10⁶ BTU	–	
ELECTRICITY	$.015/KWH	–	
MAINTENANCE:			
GENERAL MAINT.	2% CAPITAL COST (159,100)	3190	
MAINT. SUPPLIES			
DIRECT LABOR:			
SUPERVISION:	10% DIRECT LABOR		
DIRECT MFG. COST		3190	
PAYROLL OVERHEAD	30% DIRECT LABOR	–	
PLANT OVERHEAD:	50% DIRECT LABOR	–	
PACKAGING:		–	
SHIPPING:		–	
INDIRECT MFG. COST		–	
DEPRECIATION:	10% CAPITAL COST (161,490)	16,149	
PROPERTY TAXES:	1% CAPITAL COST (161,490)	1,615	
INSURANCE:	0.5% CAPITAL COST (159,100)	796	
FIXED MFG COST		18,560	
TOTAL PLANT LEVEL COST		21,750	
CORPORATE OVERHEAD	3% TOTAL PLANT LEVEL COST	650	
TOTAL-MFG COST		22,400	
	PLUS GASOLINE LOSS	7,500	
	TOTAL	29,900	$600

MANUFACTURING ESTIMATE · STORAGE TANK CONTROL SCHEME

CONTROL PROCESS: GASOLINE STORAGE TANK ~ CONE ROOF ~ 100,000 Bbl CAP

PROCESS OPERATING TIME: 3 SHIFTS/DAY 365 DAYS/YR 8750 HR/YR

ITEM	DESCRIPTION	COST	
		\$/YR	\$/MBbl
RAW MATERIALS	GASOLINE LOSS ~ 99,500 GAL/YR @ \$.131/GAL = \$13,000/YR		
UTILITIES:			
COOLING WATER	$\$.03/10^3$ GAL.		
STEAM	$\$1.00/10^3$ LB		
NATURAL GAS	$\$.60/10^6$ Btu		
ELECTRICITY	\$.015/KWH		
MAINTENANCE:			
GENERAL MAINT. MAINT. SUPPLIES	2% CAPITAL COST (253,200)	5064	
DIRECT LABOR:			
SUPERVISION:	10% DIRECT LABOR		
DIRECT MFG. COST		5064	
PAYROLL OVERHEAD	30% DIRECT LABOR		
PLANT OVERHEAD:	50% DIRECT LABOR		
PACKAGING:			
SHIPPING:			
INDIRECT MFG. COST		—	
DEPRECIATION:	10% CAPITAL COST (257,000)	25,700	
PROPERTY TAXES:	1% CAPITAL COST (257,000)	2,570	
INSURANCE:	0.5% CAPITAL COST (253,200)	1,266	
FIXED MFG COST		29,536	
TOTAL PLANT LEVEL COST		34,600	
CORPORATE OVERHEAD	3% TOTAL PLANT LEVEL COST	1,040	
TOTAL MFG COST		35,640	
	PLUS GASOLINE LOSS	13,000	
		48,640	\$486
	SAY	48,600	490

MANUFACTURING ESTIMATE - STORAGE TANK CONTROL SCHEME

CONTROL PROCESS: GASOLINE STORAGE TANK ~ CONE ROOF ~ 150,000 Bbl CAP

PROCESS OPERATING TIME: 3 SHIFTS/DAY 365 DAYS/YR 8750 HR/YR

ITEM	DESCRIPTION	COST $/YR	 $/MBbl
RAW MATERIALS	GASOLINE LOSS ~ 149,500 GAL/YR @ $.131/GAL = $19,600		
UTILITIES:			
COOLING WATER	$.03/10³ GAL.		
STEAM	$1.00/10³ LB		
NATURAL GAS	$.60/10⁶ Btu		
ELECTRICITY	$.015/KWH		
MAINTENANCE:		7472	
GENERAL MAINT.	2% CAPITAL COST (373,600)		
MAINT. SUPPLIES			
DIRECT LABOR:			
SUPERVISION:	10% DIRECT LABOR		
DIRECT MFG. COST		7472	
PAYROLL OVERHEAD:	30% DIRECT LABOR		
PLANT OVERHEAD:	50% DIRECT LABOR		
PACKAGING:			
SHIPPING:			
INDIRECT MFG. COST			
DEPRECIATION:	10% CAPITAL COST (379,200)	37,920	
PROPERTY TAXES:	1% CAPITAL COST (379,200)	3,792	
INSURANCE:	0.5% CAPITAL COST (373,600)	1,868	
FIXED MFG COST		43,580	
TOTAL PLANT LEVEL COST		51,052	
CORPORATE OVERHEAD	3% TOTAL PLANT LEVEL COST	1,530	
TOTAL - MFG COST		52,582	
	SAY	52,580	
	PLUS GASOLINE LOSS	19,600	
		72,180	480
	SAY	72,200	480

A-19

MANUFACTURING ESTIMATE - STORAGE TANK: CONTROL SCHEME

CONTROL PROCESS: GASOLINE STORAGE TANK ~ PONTOON FLOATING ROOF ~ 50,000 Bbl CAP.

PROCESS OPERATING TIME: 3 SHIFTS/DAY 365 DAYS/YR 8750 HR/YR

ITEM	DESCRIPTION	COST $/YR	 $/M Bbl
RAW MATERIALS	GASOLINE LOSS: 4120 GAL/YR × $.131/GAL = $ 540/YR		
UTILITIES: COOLING WATER STEAM NATURAL GAS ELECTRICITY	 $.03/10³ GAL. $ 1.00/10³ LB $ .60/10⁶ Btu $.015/KWH		
MAINTENANCE: GENERAL MAINT. MAINT. SUPPLIES	2% CAPITAL COST (174,280)	3485	
DIRECT LABOR:			
SUPERVISION:	10% DIRECT LABOR		
DIRECT MFG. COST		3485	
PAYROLL OVERHEAD:	30% DIRECT LABOR		
PLANT OVERHEAD:	50% DIRECT LABOR		
PACKAGING:			
SHIPPING:			
INDIRECT MFG. COST		—	
DEPRECIATION:	10% CAPITAL COST (176,140)	17,615	
PROPERTY TAXES:	1% CAPITAL COST (176,140)	1760	
INSURANCE:	0.5% CAPITAL COST (174,280)	870	
FIXED MFG COST		20,245	
TOTAL PLANT LEVEL COST		23,730	
CORPORATE OVERHEAD	3% TOTAL PLANT LEVEL COST	710	
TOTAL - MFG COST		24,440	
	PLUS GASOLINE LOSS	540	
		24,980	500
	SAY	25,000	500

MANUFACTURING ESTIMATE - STORAGE TANK CONTROL SCHEME

CONTROL PROCESS: GASOLINE STORAGE TANK ~ PONTOON FLOATING ROOF ~ 100,000 BBL CAP

PROCESS OPERATING TIME: 3 SHIFTS/DAY 365 DAYS/YR 8750 HR/YR

ITEM	DESCRIPTION	COST	
		$/YR	$/MBbl:
RAW MATERIALS	GASOLINE LOSS: 6300 GAL/YR @ $.131/GAL = $825		
UTILITIES:			
COOLING WATER	$.03/10³ GAL.		
STEAM	$1.00/10³ LB		
NATURAL GAS	$.60/10⁶ Btu		
ELECTRICITY	$.015/KWH		
MAINTENANCE:			
GENERAL MAINT.	2% CAPITAL COST (274,800)	5496	
MAINT. SUPPLIES			
DIRECT LABOR:			
SUPERVISION:	10% DIRECT LABOR		
DIRECT MFG. COST		5496	
PAYROLL OVERHEAD	30% DIRECT LABOR		
PLANT OVERHEAD:	50% DIRECT LABOR		
PACKAGING:			
SHIPPING:			
INDIRECT MFG. COST		—	
DEPRECIATION:	10% CAPITAL COST (278,920)	27,892	
PROPERTY TAXES:	1% CAPITAL COST (278,920)	2789	
INSURANCE:	0.5% CAPITAL COST (274,800)	1374	
FIXED MFG COST		32055	
TOTAL PLANT LEVEL COST		37,551	
CORPORATE OVERHEAD	3% TOTAL PLANT LEVEL COST	1,126	
		38677	
TOTAL-MFG COST	SAY	38,680	
	PLUS GASOLINE LOSS	825	
		39,505	395
	SAY	39,500	.400

MANUFACTURING ESTIMATE - STORAGE TANK CONTROL SCHEME

CONTROL PROCESS: GASOLINE STORAGE TANK ~ PONTOON FLOATING ROOF ~ 150,000 Bbl CAP

PROCESS OPERATING TIME: 3 SHIFTS/DAY 365 DAYS/YR 8750 HR/YR

		COST	
ITEM	DESCRIPTION	$/YR	$/M Bbl
RAW MATERIALS	GASOLINE LOSS: 8820 GAL/YR @ $.131/GAL = $1160		
UTILITIES:			
COOLING WATER	$.03/10³ GAL.		
STEAM	$1.00/10³ LB		
NATURAL GAS	$.60/10⁶ Btu		
ELECTRICITY	$.015/KWH		
MAINTENANCE:			
GENERAL MAINT.	2% CAPITAL COST (397,500)	7950	
MAINT. SUPPLIES			
DIRECT LABOR:			
SUPERVISION:	10% DIRECT LABOR		
DIRECT MFG. COST		7950	
PAYROLL OVERHEAD	30% DIRECT LABOR		
PLANT OVERHEAD:	50% DIRECT LABOR		
PACKAGING:			
SHIPPING:			
INDIRECT MFG. COST		—	
DEPRECIATION:	10% CAPITAL COST (403,460)	40,346	
PROPERTY TAXES:	1% CAPITAL COST (403,460)	4,035	
INSURANCE:	0.5% CAPITAL COST (397,500)	1,988	
FIXED MFG COST		46,369	
TOTAL PLANT LEVEL COST		54,319	
CORPORATE OVERHEAD	3% TOTAL PLANT LEVEL COST	1630	
TOTAL-MFG COST		55,949	
	Say	55,950	
	PLUS GASOLINE LOSS	1160	
		57,110	380
	SAY	57,100	380

MANUFACTURING ESTIMATE - STORAGE TANK CONTROL SCHEME

CONTROL PROCESS: GASOLINE STORAGE TANK ~ INTERNAL COVER/CONE ROOF - 50,000 BBL CAP

PROCESS OPERATING TIME: 3 SHIFTS/DAY 365 DAYS/YR 8750 HR/YR

ITEM	DESCRIPTION	COST	
		\$/YR	\$/MBbl
RAW MATERIALS	GASOLINE LOSS: 11,450 GAL/YR @ \$.131/GAL - \$1500		
UTILITIES:			
COOLING WATER	\$.03/10^3 GAL.		
STEAM	\$1.00/10^3 LB		
NATURAL GAS	\$.60/10^6 BTU		
ELECTRICITY	\$.015/KWH		
MAINTENANCE:			
*GENERAL MAINT.	2% CAPITAL COST (192,600)	3852	
MAINT. SUPPLIES			
DIRECT LABOR:			
SUPERVISION:	10% DIRECT LABOR		
DIRECT MFG. COST		3852	
PAYROLL OVERHEAD:	30% DIRECT LABOR		
PLANT OVERHEAD:	50% DIRECT LABOR		
PACKAGING:			
SHIPPING:			
INDIRECT MFG. COST			
* DEPRECIATION:	10% CAPITAL COST (195,160)	19516	
* PROPERTY TAXES:	1% CAPITAL COST (195,160)	1952	
* INSURANCE:	0.5% CAPITAL COST (192,600)	963	
FIXED MFG COST		22431	
TOTAL PLANT LEVEL COST		26,283	
CORPORATE OVERHEAD	3% TOTAL PLANT LEVEL COST	788	
TOTAL-MFG COST		27,071	
	SAY	27,070	
	PLUS GASOLINE LOSS	1500	
		28,570	570
	SAY	28,600	570
* NOTE:	COST BASED ON CAPITAL FOR CONE ROOF TANK & CONVERSION TO ROOF	INTERNAL FLOATING	

MANUFACTURING ESTIMATE - STORAGE TANK CONTROL SCHEME

CONTROL PROCESS: GASOLINE STORAGE TANK ~ INTERNAL COVER/CONE ROOF ~ 100,000 Bbl CAP.

PROCESS OPERATING TIME: 3 SHIFTS/DAY 365 DAYS/YR 8750 HR/YR

ITEM	DESCRIPTION	COST	
		$/YR	$/MBbl
RAW MATERIALS	GASOLINE LOSS: 19,600 GAL/YR $.131/GAL = $2560		
UTILITIES:			
COOLING WATER	$.03/10³ GAL.		
STEAM	$1.00/10³ LB		
NATURAL GAS	$.60/10⁶ Btu		
ELECTRICITY	$.015/KWH		
MAINTENANCE: * GENERAL MAINT. MAINT. SUPPLIES	2% CAPITAL COST (306,700)	6134	
DIRECT LABOR:			
SUPERVISION:	10% DIRECT LABOR		
DIRECT MFG. COST		6134	
PAYROLL OVERHEAD	30% DIRECT LABOR		
PLANT OVERHEAD:	50% DIRECT LABOR		
PACKAGING:			
SHIPPING:			
INDIRECT MFG. COST			
* DEPRECIATION:	10% CAPITAL COST (310,770)	31077	
* PROPERTY TAXES:	1% CAPITAL COST (310,770)	3108	
* INSURANCE:	0.5% CAPITAL COST (306,700)	1534	
FIXED MFG COST		35719	
TOTAL PLANT LEVEL COST		41,953	
CORPORATE OVERHEAD	3% TOTAL PLANT LEVEL COST	1256	
TOTAL MFG COST		43,109	
	SAY	43,110	
	PLUS GASOLINE LOSS	2,560	
		45,670	456
	SAY	45,600	460

* NOTE: COST BASED ON CAPITAL FOR CONE ROOF TANK & CONVERSION TO INTERNAL FLOATING ROOF

MANUFACTURING ESTIMATE - STORAGE TANK CONTROL SCHEME

CONTROL PROCESS: Gasoline Storage Tank ~ Internal Cover/Cone Roof ~ 150,000 Bbl Cap

PROCESS OPERATING TIME: 3 SHIFTS/DAY 365 DAYS/YR 8750 HR/YR

ITEM	DESCRIPTION	COST $/YR	 $/MBbl
RAW MATERIALS	GASOLINE LOSS: 29,800 GAL/YR @ $.131/GAL = $3900		
UTILITIES:			
COOLING WATER	$.03/$10^3$ GAL.		
STEAM	$1.00/$10^3$ LB		
NATURAL GAS	$.60/$10^6$ Btu		
ELECTRICITY	$.015/KWH		
MAINTENANCE:			
* GENERAL MAINT.	2% CAPITAL COST (441,600)	8832	
MAINT. SUPPLIES:			
DIRECT LABOR:			
SUPERVISION:	10% DIRECT LABOR		
DIRECT MFG. COST		8832	
PAYROLL OVERHEAD:	30% DIRECT LABOR		
PLANT OVERHEAD:	50% DIRECT LABOR		
PACKAGING:			
SHIPPING:			
INDIRECT MFG. COST			
* DEPRECIATION:	10% CAPITAL COST (447,540)	44754	
* PROPERTY TAXES:	1% CAPITAL COST (447,540)	4475	
* INSURANCE:	0.5% CAPITAL COST (441,600)	2208	
FIXED MFG COST		51437	
TOTAL PLANT LEVEL COST		60,269	
CORPORATE OVERHEAD	3% TOTAL PLANT LEVEL COST	1,808	
		62,077	
TOTAL MFG COST	SAY	62,080	
	PLUS GASOLINE LOSS	3900	
		65,980	440
	SAY	66,000	440

* NOTE: COST BASED ON CAPITAL FOR CONE ROOF TANK & CONVERSION TO INTERNAL FLOATING ROOF

July 13, 1971

Singmaster & Breyer
219 East 44th Street
New York, New York 10017

Attention: Mr. Samuel Martin

Gentlemen:

Confirming your telephone conversation with our Mr. E.H. Bodinson on budgetary prices for Cone Roof Tanks and Pontoon Floaters, as well as our , we wish to adivse you of budgetary figures as follows:

	Cone Roof Tanks	Pontoon Floaters	Hammondflotes
			In existing Cone Roof Tanks
95'ϕ x 40'	$108,000	$120,000	$29,000
120'ϕ x 48'	$188,000	$208,000	$40,000
150'ϕ x 48'	$274,000	$300,000	$56,000

The above prices are basically for the Eastern part of the United States. It must be understood that those prices, given above, are simply for budgetary and are not intended to be used as a selling price.

Very truly yours,

July 9, 1971

Singmaster & Breyer
235 East 42nd Street
New York, New York 10017

Attention: Mr. Sam Martin

Storage Tanks

Dear Mr. Martin:

In response to your recent verbal inquiry, we are attaching a separate tabulation confirming the verbal budget prices given you for the various sized storage tanks under consideration.

These prices are for tanks with standard fittings erected on foundations provided by others, assuming average erection conditions. We trust that this is adequate for your needs at this time. Should you require anything further, please feel free to call on us.

Yours very truly,

7-7-71
71-516-1

BUDGET PRICES

	WEIGHT	PRICE
CAPACITY: 50 000 BBL		
SIZE: 90 x 48		
CONE ROOF TANK	389.000#	95.000$
INTERNAL FLOATING ROOF	66.000	38.000
FLOATING ROOF TANK	405.300	110.000
CAPACITY: 100 000 BBL		
SIZE: 134 x 40		
CONE ROOF TANK	697.400	155.000
INTERNAL FLOATING ROOF	141.000	65.000
FLOATING ROOF TANK	711.400	172.000
CAPACITY: 150 000 BBL		
SIZE: 150 x 48		
CONE ROOF TANK	1.047.300	225.000
INTERNAL FLOATING ROOF	176.000	80.000
FLOATING ROOF TANK	1.045.900	240.000

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APPENDIX B

CALCULATIONS, QUOTES AND CORRESPONDENCE

INCINERATION

TABLE OF CONTENTS

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INCINERATION PROCESS CALCULATIONS B-2

INSTALLED CAPITAL COST ESTIMATES B-22

OPERATING COST ESTIMATES B-58

VENDOR BUDGET QUOTES B-94

PROCESS CONCEPT FOR CONTROL OF HEXANE AND BENZENE FUMES FROM A PAINT BAKING OVEN VIA INCINERATION

A paint baking oven exhausts a 50/50 weight percent mixture of benzene and hexane vapors in air at concentrations of 15% and 25% of the lower explosive limit (LEL) and a temperature of 375°F.

Air pollution regulations require that all hydrocarbon emissions be reduced by 90% by conversion to carbon dioxide and water vapor before exhausting to the atmosphere.

Economic evaluation of thermal and catalytic incinerators both with and without heat recovery systems is performed for oven exhaust volumes of 1,000, 10,000 and 20,000 SCFM. The oven is assumed to operate two shifts per day, 365 days per year.

SINGMASTER & BREYER
CHEMICAL & METALLURGICAL PROCESS ENGINEERS

COMPUTATION SHEET
J. O. No. PS-228
SHEET No. B-2 OF
DATE 7/20/71
COMP. BY STM C'K'D BY

NAME OF COMPANY MSA RESEARCH CORP.

SUBJECT INCINERATOR STUDY - BASIS (25% LEL)

BASIS OF EVALUATION

A PAINT BAKING OVEN EXHAUSTS A 50/50 MIXTURE BY WEIGHT OF HEXANE & BENZENE AT 25% LOWER EXPLOSIVE LIMIT (LEL) CONCENTRATION IN AIR AT 375°F. 90% BY WEIGHT OF THE HYDROCARBON MIXTURE IS TO BE CONVERTED TO CO_2 AND H_2O↑. FUEL WILL BE NATURAL GAS.

EVALUATE THE PROCESS REQUIREMENTS OF THERMAL AND CATALYTIC INCINERATION SYSTEMS BOTH WITH AND WITHOUT HEAT RECOVERY UNITS AT CAPACITIES OF 1,000, 10,000, AND 20,000 SCFM.

LEL: BENZENE = 1.5% IN AIR BY VOLUME
HEXANE = 1.2% " " " "
} L.E.L. VALUES P 1868 3RD ED. PERRY'S - CHE. HANDBOOK

AVG SPECIFIC HEATS: (Btu/lb °F)

	75° → 1450°
METHANE	.82
HEXANE	.75
* BENZENE	.60
OXYGEN	.24
NITROGEN	.26
CARBON DIOXIDE	.25
WATER VAPOR	.50

* BENZENE SP.HT. EVALUATED BY USE OF U.O.P. CHARACTERIZATION FACTOR AND CCP CHART FOR SP. HT OF HYDROCARBON GASES AT 1 ATM

$K = \frac{(T_B)^{1/3}}{G}$; K = U.O.P. CHAR. FACTOR
T_B = AVG. BOILING POINT °RANKINE @ 1 ATM
G = SP. GR @ 60°F

$K = (636)^{1/3}/.88 = 9.8$
$C_P = .60$

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SUBJECT INCINERATOR STUDY
(25% LEL)

INCINERATOR REACTIONS:

COMPOUND	HEAT OF COMBUSTION		CHEMICAL REACTION
HEXANE	19,391 Btu/lb		$C_6H_{14} + 9.5O_2 \rightarrow 6CO_2 + 7H_2O\uparrow$
		M.W. →	86 304 264 126
BENZENE	17,446 Btu/lb		$C_6H_6 + 7.5O_2 \rightarrow 6CO_2 + 3H_2O$
		M.W →	78 240 264 54
METHANE	21,502 Btu/lb		$CH_4 + 2O_2 \rightarrow CO_2 + 2H_2O$
		MW →	16 64 44 36

THERMAL INCINERATION WITHOUT HEAT RECOVERY:

MATERIAL BALANCE: BASIS - 1000 SCFM OVEN EXHAUST

25% LEL: HEXANE IS CONTROLLING WITH LOWER 1.2% LEL

$\frac{.012}{4} = .003$ ~ 3 FT³ SOLVENT / 997 AIR

AVG. M.W.; $\frac{100}{78} + \frac{100}{86} = 1.28 + 1.16 = 2.44$ MOLES

200/2.44 = 82 AVG MW

$\frac{3}{359} \times \frac{492}{520} \times 82 \times 60 = 38.8$ LB/HR SOLVENT

AIR = $\frac{29}{359} \times \frac{492}{520} \times 997 \times 60 = 4560$ LB/HR AIR,

$\frac{4560}{29} = 157$ MOLES/HR AIR

33 MOLES/HR $O_2 \times 32 = 1056$ LB/HR O_2

124 MOLES/HR $N_2 \times 28 = 3470$ LB/HR N_2

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SUBJECT INCINERATOR STUDY - THERMAL w/o HEAT RECOVERY (25% LEL)

MATERIAL BALANCE (CON'T)

OVEN EXHAUST
HEXANE = 19.4 LB/HR
BENZENE = 19.4 LB/HR
O_2 = 1056 LB/HR
N_2 = 3470 LB/HR

FUEL
CH_4 (TO BE DETERMINED)

INCINERATOR EXHAUST @ 1450
HEXANE = 1.9 LB/HR
BENZENE = 1.9 LB/HR
NITROGEN = 3470 LB/HR
O_2 = 940 - 4 CH_4 LB/HR
CO_2 = 113 + 2.75 CH_4 LB/HR
H_2O = 37.8 + 2.25 CH_4 LB/HR

ENERGY BALANCE:

AVG HEAT OF COMBUSTION HEXANE/BENZENE = $\frac{19,391 + 17,446}{2} = 18,418 \frac{Btu}{LB}$

HEAT VALUE/SCF @ 25% LEL (HEXANE/BENZENE)

$$\frac{82}{359} \times \frac{492}{520} \times \frac{.012}{4} \times 18,418 = 12.0 \text{ Btu/SCF}$$

AVG SP. HT. INLET GAS

	LB/HR	WT %	x	SP. HT		
C_6H_{14} -	19.4	.005	x	.75	=	.0040
C_6H_6 -	19.4	.005	x	.60	=	.0030
O_2 -	1056.0	.23	x	.24	=	.0552
N_2	3470.0	.76	x	.26	=	.1970
	4564.8					.2592

AVG Cp = .26 $\frac{Btu}{LB\ °F}$

INLET GAS DENSITY - SCF CONDITIONS = $\frac{4565}{60,000}$ = .076

THEREFORE M.WT ≈ AIR ≈ 29

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SUBJECT INCINERATOR STUDY - THERMAL w/o HEAT RECOVERY (25% LEL)

HEAT BALANCE (CONT)

TEMP. RISE DUE TO SOLVENT COMBUSTION @ 90% CONVERSION

$$\frac{12\ \frac{Btu}{SCF}\ (.9)}{.076\ \frac{LB}{SCF} \times .26\ \frac{Btu}{\cancel{LB}\ °F}} = 545\ °F \text{ FROM INLET GASES}$$

RISE REQD FROM NAT. GAS FUEL = (1450 - 545 - 375) = 530°F

1. ASSUME - GAS DENSITY, MOL. WT., AND SP. HT. OF INCINERATOR EXHAUST GASES AT SCF CONDITIONS IS EQUAL TO THAT OF INLET GASES
2. ASSUME SCF OF INLET & OUTLET GASES IS ESSENTIALLY EQUAL

$$.076\ \frac{\cancel{LB}}{\cancel{SCF}} \times .26\ \frac{Btu}{\cancel{LB}\,\cancel{°F}} \times 530\cancel{°F} \times 1000\ \frac{\cancel{SCF}}{\cancel{MIN}} \times 60\ \frac{\cancel{MIN}}{HR} = 629{,}000\ Btu/HR$$

$$\frac{629{,}000}{21{,}502} = 29.2\ LB/HR\ CH_4$$

CALCULATION CHECK

$$\text{VOLUME IN} = 60{,}000 + \frac{29.2}{16} \times 359 \times \frac{520}{492} = 60{,}000 + 692 = 60{,}692\ SCFH$$

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SUBJECT INCINERATOR STUDY-THERMAL w/o HEAT RECOVERY
(25% LEL)

CALCULATION CHECK (CONT) - MATL'S OUT

	LB/HR	WT %	x	Cp		MOLES/HR
HEXANE	1.9	.0005	x	.75	–	.0463
BENZENE	1.9	.0005	x	.60	–	
NITROGEN	3470.0	.758	x	.26	.197	124.00
O_2	823.0	.180	x	.24	.043	25.70
CO_2	193.0	.041	x	.25	.010	4.39
H_2O	104.0	.020	x	.50	.010	5.78
	4593.8	1.0000			.26	159.9163

$$\text{VOL OUT} \sim 159.9 \times 359 \times \frac{520}{492} = 61{,}000$$

BECAUSE Δ VOLUME ACROSS INCINERATOR AT SCFM CONDITIONS IS NEGLIGIBLE & ΔC_p ACROSS INCINERATOR IS ZERO, THE ASSUMPTIONS ON PAGE 4 ARE VALID

THERMAL INCINERATOR w/o HEAT RECOVERY
AUXILIARY HEAT REQUIREMENT: [illegible]

629,000 Btu/HR / 1000 SCFM PROCESSED

NOTE: THIS CALCULATION METHOD PRODUCES VALUES WITHIN 2.5% OF THE RIGOROUS METHOD WHICH EMPLOYS HEATS OF REACTION AT ELEVATED TEMPERATURES.

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SUBJECT INCINERATOR STUDY - THERMAL WITH PRIMARY HEAT RECOVERY
(25% LEL)

HEAT BALANCE: BASIS - 1000 SCFM OVEN EXHAUST GASES

OVEN EXHAUST TEMP = 375°F INCINERATOR EXHAUST TEMP = 1450°F

FROM PAGE 4 - TEMP. RISE DUE TO COMBUSTION GASES = 530°F

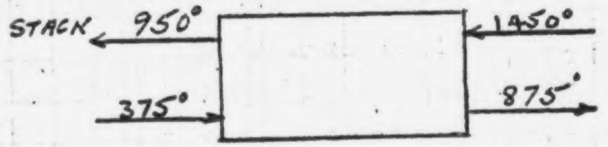
HEAT EXCHANGER EFFICIENCY ≈ 46-47% PER QUOTES

ΔT @ 100% EFFICIENCY

$(1450 - 375) = 1075°F$

$.465 (1075) = 500°F$

THEREFORE THE RISE THROUGH
THE EXCHANGER 375 → 875



TEMP RISE REQD BY FUEL = 1450 - 530 - 875 = 45°F

HEAT REQUIREMENT:

$$.076 \frac{LB}{SCF} \times .26 \frac{Btu}{LB\,°F} \times 45°F \times 1000 \frac{SCF}{MIN} \times 60 \frac{MIN}{HR} = 53{,}200 \frac{Btu}{HR}$$

THERMAL INCINERATOR w/ HEAT RECOVERY
AUXILIARY HEAT REQUIREMENT:

53,200 Btu/HR/1000 SCFM PROCESSED

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COMPUTATION SHEET
J. O. No. PS-228
SHEET No. B-8 OF
DATE 7/21/71
COMP. BY STM C'K'D BY

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SUBJECT INCINERATOR STUDY - SUMMARY OF FUEL & POWER REQUIREMENTS - THERMAL INCINERATION WITH & WITHOUT PRIMARY HEAT RECOVERY (25% LEL)

INCINERATOR CAPACITY (SCFM)	1,000	10,000	20,000
NATURAL GAS REQUIREMENT:			
WITHOUT HEAT RECOVERY, (Btu/Hr)	629,000	6.29×10^6	12.58×10^6
WITH PRIMARY HEAT RECOVERY (Btu/Hr)	53,200	$.532 \times 10^6$	1.064×10^6
* HORSE POWER REQUIREMENT:			
WITHOUT HEAT RECOVERY	3 HP	25 HP	50 HP
WITH HEAT RECOVERY	5 HP	50 HP	100 HP

* Costs of Blowers, Motors and Auxiliary Equipment (In conjunction with above HP requirements)

WITHOUT HEAT RECOVERY	$1,000	$4,000	$7,500
WITH HEAT RECOVERY	$1,400	$5,500	$10,000

* MAINTENANCE - 5%

* VERBAL QUOTE:
HEAT EXCHR./1000 SCFM THERMAL UNIT - $4,400 WT ~ 5000 LBS

* INSTALLATION TIME 8-10 WKS SAY 3 MONTHS

[illegible] VERB[illegible] WILL BE CONFIRMED BY [illegible] P.

* NOTE: THESE VALUES FROM VERBAL QUOTES

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COMPUTATION SHEET

J. O. No. PS-228
SHEET No. B-9 OF
DATE 8/3/71
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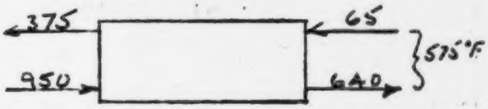
SUBJECT Incinerator Study - Thermal with Primary & Secondary Heat Recovery
(25% LEL)

BASIS: 1000 SCFM OVEN MAKE UP & EXHAUST AT 375°F

SECONDARY HEAT EXCHANGER:



THERMAL EFF = $\frac{310}{885}$ = 35%

$U_{AIR/AIR}$ = 2-8 Btu/Hr Ft² °F FROM PERRY'S

USE U = 5 Btu/Hr Ft² °F

MAKE UP AIR:

$\frac{1000}{359} \times \frac{492}{520} \times 29 \times 60 = 4550$ $\frac{\text{LB}}{\text{HR}}$ AIR ~ 1000 SCFM

45,500 $\frac{\text{LB}}{\text{HR}}$ AIR ~ 10,000 SCFM

91,000 $\frac{\text{LB}}{\text{HR}}$ AIR ~ 20,000 SCFM

HEAT EXCHANGER COST:

1) PRIMARY HEAT EXCHANGER COST VS AREA ESTIMATE —

* UNIT SIZE	COST = (UNIT WITH EXCHR – UNIT WITHOUT)	AREA
a) 20,000 SCFM	$32,500	4120
b) 10,000 SCFM	$17,500	2060
c) 1000 SCFM	$4400 COST EXTRAPOLATED FROM a) & b)	~206

PRIMARY HT EXCHR ΔT_{LM} = 575°F, RISE = 500°F, U = 5

q = 4550 (.26)(500) = 592,000 Btu/Hr / 1000 SCFM

$A = \frac{592,000}{5 \times 575} = 206 \text{ FT}^2$

* A LOG/LOG PLOT COST VS AREA FROM THIS DATA TO BE USED TO ESTIMATE SECONDARY HEAT EXCHANGER COST

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SUBJECT INCINERATOR STUDY - THERMAL WITH PRIMARY & SECONDARY (25% LEL) HEAT RECOVERY

2) SECONDARY HEAT EXCHANGER $\Delta T_{LM} = 575°F$, RISE = 310, U = 5

$$q = 4550(.26)(310) = 367,000 \text{ Btu/HR}$$

$$A = \frac{367,000}{5(575)} = 128 \text{ FT}^2$$

RATE	AREA	COST
1000 SCFM	128	$ 3,800
10,000 SCFM	1280	15,000
20,000 SCFM	2560	23,000

NATURAL GAS FUEL SAVINGS: (AT (BAKING OVEN)

$$(4550 + CH_4)(.26)(310) = CH_4(21,502)$$

$$(4550 + CH_4)80.5 = CH_4(21,502)$$

$$4550(80.5) = (21,502 - 80.5)CH_4$$

$$CH_4 = \frac{366,000}{21,422} = 17.1 \text{ LB/HR } CH_4$$

$$17.1(21,502) = 368,000 \frac{\text{Btu}}{\text{Hr}} / 1,000 \text{ SCFM}$$

SAVINGS OVEN FUEL
368,000 $\frac{\text{Btu}}{\text{Hr}}$ /1000 SCFM

MAKE UP AIR FAN COST (FROM pg B-8)

RATE, (SCFM)	COST	HP
1,000	1,400	5
10,000	5,500	50
20,000	10,000	100

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SHEET No. B-11 OF
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SUBJECT INCINERATOR STUDY - CATALYTIC INCINERATION (25% LEL)
W/O HEAT RECOVERY

MATERIAL & ENERGY BALANCE

INCINERATOR EXHAUST TEMPERATURE ~ 1200°F

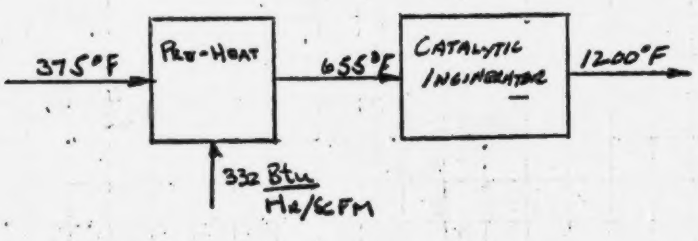
FROM PG B-5 TEMP. RISE AVAILABLE FROM INLET GASES @ 90% CONVERSION ~ 545°F

THEREFORE TEMPERATURE RISE REQ'D AT PREHEAT:

$$1200 - 545 - 375 = 280°F$$

HEAT REQD PER SCF

$$.076 \frac{\cancel{LB}}{SCFM} \times .26 \frac{Btu}{\cancel{LB°F}} \times 280\cancel{°F} \times 60 \frac{MIN}{HR} = 332 \frac{Btu}{HR/SCFM}$$



HEAT REQUIREMENTS

CAPACITY	Btu/Hr
1000 SCFM	.332 x 10^6
10,000 SCFM	3.32 x 10^6
20,000 SCFM	6.64 x 10^6

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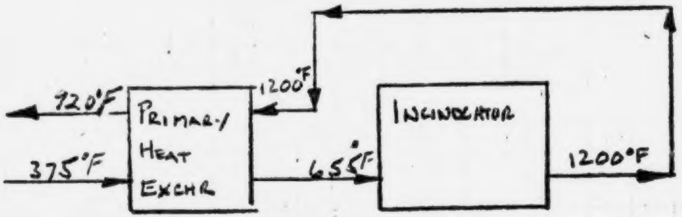
SUBJECT INCINERATOR STUDY - CATALYTIC WITH PRIMARY HEAT RECOVERY (25% LEL)

MATERIAL & ENERGY BALANCE

FROM PP B-5, B-11 : TEMP RISE FEED = 545 °F
INCINERATOR EXHAUST = 1200 °F

BASIS: 1000 SCFM



$q = .26(.076)(1000)(60)(280) = 332{,}000$ Btu/HR

$\Delta T = 545 \quad U = 5$ Btu/HR FT² °F

$$A = \frac{332{,}000}{(5)(545)} = 122 \text{ FT}^2$$

HEAT REQUIREMENTS & HEAT EXCHR. DATA

CAPACITY	Btu/HR	HEAT EXCHANGER AREA	HEAT EXCHANGER *COST
1000 SCFM	-0-	122	** 3,500
10,000 SCFM	-0-	1220	11,000
20,000 SCFM	-0-	2440	23,000

* BY SUBTRACTION FROM VERBAL & WRITTEN QUOTES
** FROM LOG/LOG PLOT

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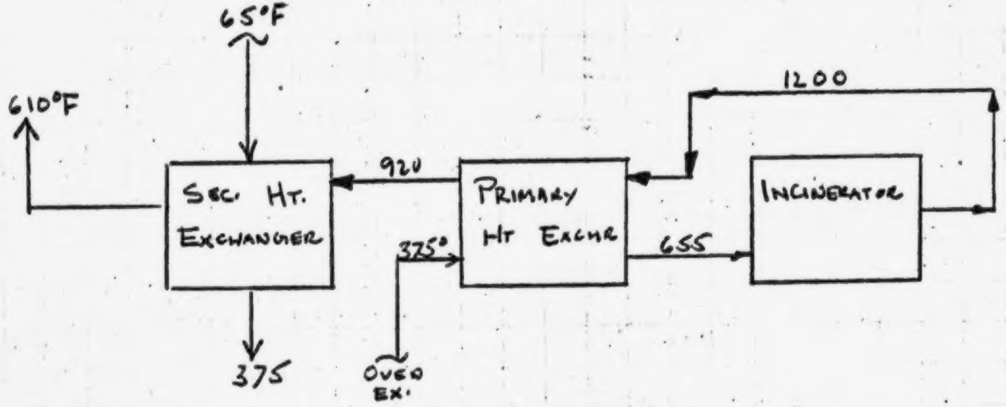
SUBJECT INCINERATOR STUDY - CATALYTIC WITH PRIMARY & SEC HEAT RECOVERY (25% LEL)

MATERIAL & ENERGY BALANCE

FROM PP B-5,8-11 : TEMP RISE FEED = 545
INCINERATOR EXHAUST = 1200
MAKE UP. AIR = 375

BASIS: 1000 SCFM


65°F
610°F
1200
920
SEC. HT. EXCHANGER
PRIMARY HT EXCHR
INCINERATOR
375°
655
375
OVEN EX.

HEAT REQUIREMENTS & HEAT EXCHR DATA

		PRI. HT EXCHR		SEC. HT EXCHR	
CAPACITY	Btu/Hr	AREA	COST	AREA	COST
1000 SCFM	-	122	** 3,500	135	** 3,800
10,000 SCFM	-	1220	11,000	1350	15,000
20,000 SCFM	-	2400	23,000	2700	24,000

$$q = .076(.26)(1000)(60)(310) = 367{,}000 \ \frac{Btu}{hr}$$

$$A = \frac{367{,}000}{5(545)} = 135$$

** FROM LOG/LOG PLOT

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COMPUTATION SHEET
J. O. No. PS-228
SHEET No. B-14 OF
DATE 8/17/71
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SUBJECT INCINERATOR STUDY - SUMMARY - FUEL, POWER, HEAT EXCHANGER, CATALYST, REQUIREMENTS - CATALYTIC INCINERATORS WITH AND WITHOUT PRIMARY & SECONDARY HEAT RECOVERY (25% LEL)

CAPACITY, SCFM		1000	10,000	20,000
INCINERATOR & HT. EXCHR(S)				
*WITHOUT HT RECRY CAPITAL EQUIP. COST		$15,000	$96,000	$178,000
WITH PRIMARY HT. *RECOVERY, CAPITAL EQUIP COST		$18,500 (1)	$107,000	$201,000
*WITH PRI./SEC. HT RECOVERY, CAP. EQUIP COST		$22,300 (2)	$122,000 (2)	$225,000 (2)
*CATALYST COST ($/SCFM CAP)		16	7	7
FAN REQUIREMENT				
W/O HT REC.:	COST	$1,000	$4000	$7500
	HP	3	25	50
PRI. HT REC.:	COST	$1400	$5500	$10,000
	HP	5	50	100
SEC. HT REC. #1	COST	$1400	$5500	$10,000
(2 REQ'D)	HP	5	50	100
FUEL (BTU/HR)				
W/O HT RECOVERY		$.332\times10^6$	3.32×10^6	6.64×10^6

(1) ESTIMATED ADDITIONAL COST FOR HEAT EXCHANGER FROM LOG/LOG PLOT OF PRICE DIFFERENTIAL OF 10M & 20M SCFM UNITS WITH & WITHOUT PRIMARY HEAT RECOVERY

(2) ESTIMATED COST OF SECONDARY HEAT EXCHANGER FROM LOG/LOG PLOT IN (1) ABOVE BASED ON HEATING SURFACE REQUIREMENTS

* PRICES ARE VERBAL QUOTES

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COMPUTATION SHEET
J. O. No. PS-228
SHEET No. B-15 OF
DATE 8/18/71
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SUBJECT INCINERATOR STUDY -
(15% LEL)

BASIS OF EVALUATION

A PAINT BAKING OVEN EXHAUSTS A 50/50 MIXTURE BY WEIGHT OF HEXANE & BENZENE AT 15% LOWER EXPLOSIVE LIMIT (LEL) CONCENTRATION IN AIR AT 375°F. 90% BY WEIGHT OF THE HYDROCARBON MIXTURE IS TO BE CONVERTED TO CO_2 AND H_2O. FUEL WILL BE NATURAL GAS

EVALUATE THE PROCESS REQUIREMENTS OF THERMAL AND CATALYTIC INCINERATION SYSTEMS WITH AND WITHOUT HEAT RECOVERY UNITS AT CAPACITIES OF 1,000, 10,000, AND 20,000 SCFM.

LEL: BENZENE = 1.5% IN AIR BY VOLUME
HEXANE = 1.2% IN AIR BY VOLUME
} LEL VALUES p. 1868 3RD ED. PERRY'S CHE. HANDBOOK

HEXANE IS CONTROLLING:

.012 (.15) = .0018 ~ .9 FT³ HEXANE
.9 FT³ BENZENE
998.2 FT³ BENZENE

SCF CONDITIONS

DENSITY:

$$\frac{82}{359} \times \frac{492}{520} \times 1.8 = .383 \text{ LB}/1000\text{ SCF} \qquad \rho = \frac{76.4}{1000} \approxeq .076$$

$$\frac{29}{359} \times \frac{492}{520} \times 998.2 = 76.0 \text{ LB}/1000\text{ SCF}$$

HEAT VALUE:

$$\frac{82}{359} \times \frac{492}{520} \times .0018 \times 18{,}418 = 7.2 \text{ Btu/FT}^3$$

TEMP RISE:

$$\frac{7.2 \frac{\text{Btu}}{\text{FT}^3} \times .9}{.076 \frac{\cancel{\text{LB}}}{\cancel{\text{FT}^3}} \times .26 \frac{\text{Btu}}{\cancel{\text{LB}}\ °\text{F}}} = \Delta T = 330°\text{F}$$

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SUBJECT Incinerator Study - Thermal
(15% LEL)

Thermal - w/o Ht. Recovery

1400 - 330 - 375 = 695°F Rise Reqd from fuel

Req'd Ht. Input

$\cdot 076 \times \cdot 26 \times 695 = 13\cdot 7 \ \frac{Btu}{SCF}$

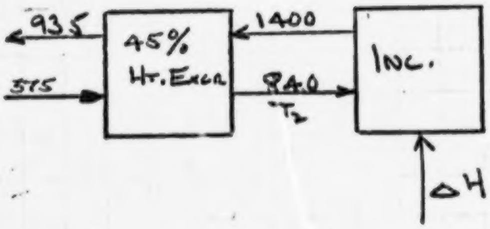
ΔH:

1000 SCFM = $\cdot 822 \times 10^6$ Btu/Hr

10,000 SCFM = $8\cdot 22 \times 10^6$ Btu/Hr

20,000 SCFM = $16\cdot 44 \times 10^6$ Btu/Hr

Thermal With Pri. Ht. Recry



$\cdot 45(1400-375)+375 = T_2 = 837°F \approx 840$

1400 - 330 - 840 = 230°F Rise Req'd

Reqd Heat Input

$\cdot 076 \times \cdot 26 \times 230 = 4\cdot 55 \ \frac{Btu}{SCF}$

ΔH:

1000 SCFM - $.273 \times 10^6$ Btu/Hr

10,000 SCFM - $2\cdot 73 \times 10^6$ Btu/Hr

20,000 SCFM - $5\cdot 46 \times 10^6$ Btu/Hr

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COMPUTATION SHEET

J. O. No. PS-228

SHEET NO. B-17 OF

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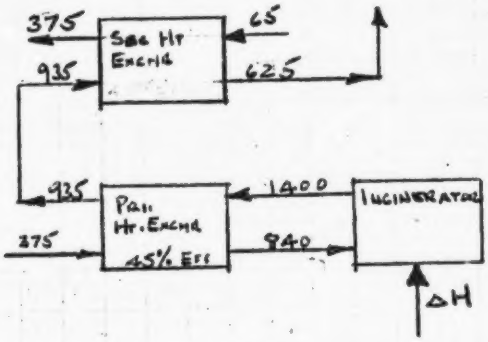
SUBJECT Incinerator Study - Thermal
(15% LEL)

THERMAL INCINERATION WITH PRIMARY & SECONDARY HEAT RECOVERY

ΔH: (Incinerator)
1000 SCFM – .273 x10⁶ Btu/Hr
10,000 SCFM – 2.73x10⁶ Btu/Hr
20,000 SCFM – 5.46x10⁶ Btu/Hr



ΔH: (Make-Up), Heat Saved

$q = .076 \times .26 \times 310 = 6.12 \frac{Btu}{SCF}$

1000 SCFM – .368x10⁶ Btu/Hr
10,000 SCFM – 3.68x10⁶ Btu/Hr
20,000 SCFM – 7.36x10⁶ Btu/Hr

CATALYTIC INCINERATION W/O HT. RECOVERY

Reqd Temp Rise (PreHeat):
1000 – 330 – 375 = 295°F

Heat Reqd:
$.076(.26)(295) = 5.85$ Btu/SCF

1000 SCFM ~ .350x10⁶ Btu/Hr
10,000 SCFM ~ 3.5x10⁶ Btu/Hr
20,000 SCFM ~ 7.0x10⁶ Btu/Hr

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COMPUTATION SHEET
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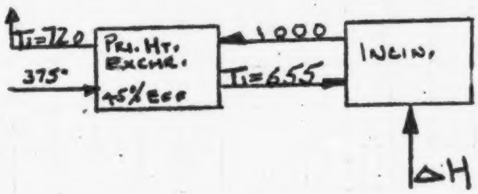
SUBJECT INCINERATOR STUDY ~ CATALYTIC
(15% LEL)

CATALYTIC INCINERATION WITH PRIMARY HEAT RECOVERY


T2=720
PRI. HT. EXCHR.
45% EFF
375°
1000
T1=655
INCIN.
ΔH

$.45(1000-375)+375 = T_1 = 656 \approx 655$

REQ'D TEMP RISE:
$1000-655-330 = 15°F$

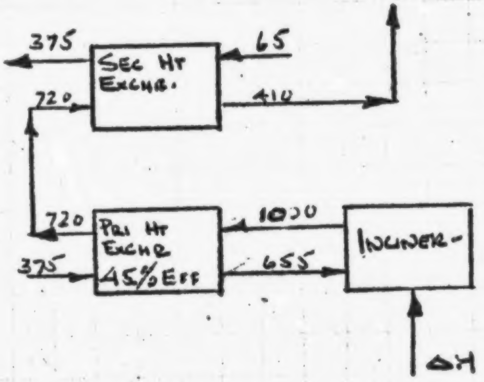
HEAT REQ'D

$.076(.26)(15) = .296$ Btu/SCF

ΔH: (INCINERATOR)

1,000 SCFM — $.0178 \times 10^6$ Btu/Hr
10,000 SCFM — $.178 \times 10^6$ Btu/Hr
20,000 SCFM — $.356 \times 10^6$ Btu/Hr

CATALYTIC INCINERATION WITH PRIMARY & SECONDARY HEAT RECOVERY


375
65
SEC HT EXCHR.
720
410
720
PRI HT EXCHR
45% EFF
1000
375
655
INCINER-
ΔH

ΔH (INCINERATOR)
1000 SCFM ~ $.0178 \times 10^6$ Btu/Hr
10 000 SCFM ~ $.178 \times 10^6$ Btu/Hr
20000 SCFM ~ $.356 \times 10^6$ Btu/Hr

ΔH (MAKE-UP), HEAT SAVED

$q = .26(.076)(310) = 6.12$ Btu/SCF

1000 SCFM ~ $.368 \times 10^6$ Btu/Hr
10,000 SCFM ~ 3.68×10^6 Btu/Hr
20,000 SCFM ~ 7.36×10^6 Btu/Hr

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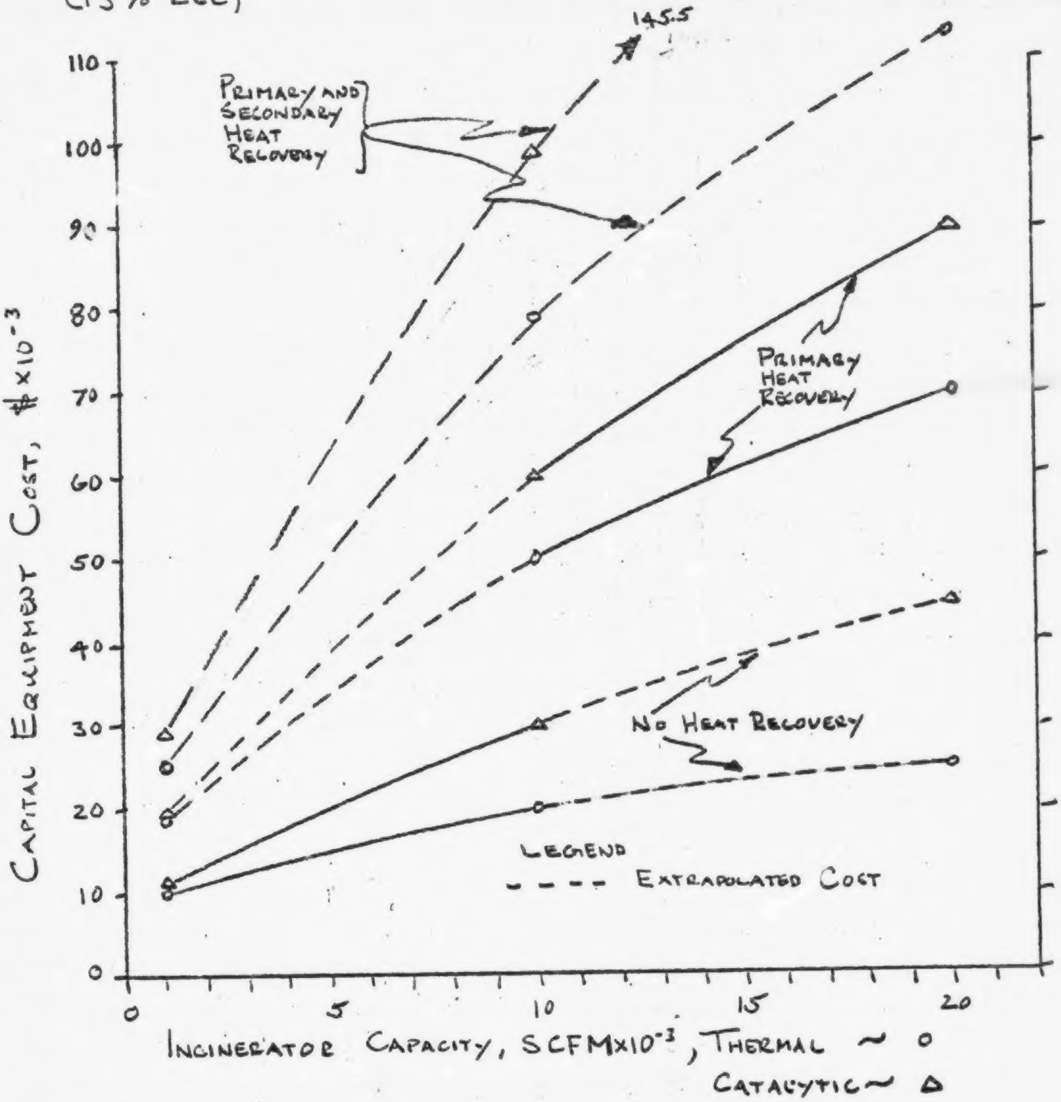
SUBJECT INCINERATOR STUDY - PLOT OF EQUIP COST
(15% LEL)



NOTE:

EXTRAPOLATED COSTS - - ACQUIRED BY LOG/LOG PLOT OF COST VS HEATING SURFACE. BASED ON $30,000 COST FOR 10,000 SCFM HEAT EXCHANGERS AND SLOPE OF COST CURVE, (COST/AREA = .56) ON LOG/LOG PLOT OF HEAT EXCHANGER COST CURVE.

HEAT EXCHANGE AREAS ARE CALCULATED ON PAGE B-20 AND SUMMARIZED ON PAGE B-21

PRICES BASED ON WRITTEN QUOTE

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COMPUTATION SHEET
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SUBJECT INCINERATOR STUDY — HT. EXCHR. AREA CALCS.
(15% LEL)

PRIMARY UNIT:

THERMAL:
$U = 5$
$\Delta T = 560$
$q = .26(.076)(465) = 9.2$

$A_{1000\ SCFM} = \frac{552,000}{5(560)} = 198\ FT^2 \approx 195\ FT^2$

$A_{10,000\ SCFM} = 1980\ FT^2 \approx 1950\ FT^2$

$A_{20,000\ SCFM} = 3960\ FT^2 \approx 3900\ FT^2$

CATALYTIC:
$U = 5$
$\Delta T = 345$
$q = .26(.076)(280) = 5.55\ \frac{Btu}{SCF}$

$A_{1000\ SCFM} = \frac{333,000}{5(345)} = 193\ FT^2 \approx 195\ FT^2$

$A_{10,000\ SCFM} = 1930\ FT^2 \approx 1950\ FT^2$

$A_{20,000\ SCFM} = 3860\ FT^2 \approx 3900\ FT^2$

SECONDARY UNIT:

THERMAL:
$U = 5$
$\Delta T = 560$
$q = 6.12\ Btu/SCF$

$A_{1000\ SCFM} = \frac{368,000}{5(560)} = 131\ FT^2 \approx 130\ FT^2$

$A_{10,000\ SCFM} = 1310\ FT^2 \approx 1300\ FT^2$

$A_{20,000\ SCFM} = 2620\ FT^2 \approx 2600\ FT^2$

CATALYTIC:
$U = 5$
$\Delta T = 345$
$q = 6.12\ Btu/SCF$

$A_{1000\ SCFM} = \frac{368,000}{5(345)} = 214\ FT^2 \approx 215\ FT^2$

$A_{10,000\ SCFM} = 2140\ FT^2 \approx 2140\ FT^2$

$A_{20,000\ SCFM} = 4280\ FT^2 \approx 4280\ FT^2$

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COMPUTATION SHEET
J. O. No. PS-228
SHEET No. B-21 OF
DATE 8/19/71
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SUBJECT INCINERATOR STUDY - SUMMARY HT EXCHR COST
(15% LE-)

PRIMARY HT. EXCHR.

THERMAL & CATALYTIC

CAPACITY	AREA	COST
1000 SCFM	195	8,500
10,000 SCFM	1950	30,000
20,000 SCFM	3900	45,000

FANS		HP
INCLUDED	-1	5
IN	1	25
COST	1	50

SECONDARY HT. EXCHR.

THERMAL:

CAPACITY	AREA	COST
1000 SCFM	130	6,500
10,000 SCFM	1300	24,000
20,000 SCFM	2600	35,000

FANS		HP
INCLUDED	-1	5
IN	-1	25
COST	-1	50

CATALYTIC:

CAPACITY	AREA	COST
1000 SCFM	215	9,000
10000 SCFM	2140	33,000
20000 SCFM	4280	48,000

FANS -		HP	COST
INCLUDED	-2	5	1400
IN COST-	-2	25	4000
ONE ONLY	-2	50	7500

* INCINERATOR EQUIPMENT COSTS (INCL HT. EXCHRS & FANS)

	CAPACITY, SCFM	w/o HT. EX	w/ PRI. HT. EXCH.	w/ PRI. & SEC. HT. EX.
THERMAL:	1000	$10,000	$18,500	$26,400
	10,000	20,000	50,000	78,000
	20,000	25,000	70,000	112,500
CATALYTIC:	1000	$11,000	$19,500	$29,900
	10,000	30,000	60,000	97,000
	20,000	45,000	90,000	145,500

INSTALLATION @ 100% COST ~ VERBAL / OXYCAT. NOT TO BE CONFIRMED

* COST VALUES - SHOWN ON PLOT PG. 8-19 CORRELATIONS.

CONSTRUCTION COST ESTIMATE

SINGMASTER & BREYER

CUSTOMER MSA Research Corp

LOCATION Evans City, Pa

PROJECT PS-228

DESCRIPTION Hydrocarbon Emmisions Control
Catalytic Incineration without Heat Recovery
(15% LEL)

PROP. NO.
CONT. NO.
MADE BY
APPROVED

ACCOUNT NUMBER	ITEM & DESCRIPTION	QUANTITY	UNIT	UNIT COSTS			ESTIMATED COST CENTS OMITTED			
				LABOR	SUB CONTR	MAT'L	LABOR	SUB CONTRACTS	MATERIALS	TOTAL
	Catalytic Incinerator* - Capacity: 1000 SCFM ~ Complete with 5 HP Blower, Controls, Interconnecting Piping & Ductwork ~ Basis ~ Budget Quote									11,000 –
	Land (Existing)									
	Excavation & Foundations									
	Piping, Ductwork, & Insulation									11,000 –
	Electrical									
	Painting									
									Sub Total	22,000 –
	Interest on Investment During Constr. (Three Months @ Prime Rate @ 6%)									330 –
									Total Cap. Cost.	22,330 –
	* Initial catalyst charge included; skid mounted unit									
									Say	22,300 –

CODE

(E 153)

DATE ______ REVISION NO. ______ REVISION DATE ______ PAGE NO. B-22

CONSTRUCTION COST ESTIMATE

SINGMASTER & BREYER

CUSTOMER MSA Research Corp

LOCATION Evans City, Pa.

PROJECT PS-228

DESCRIPTION Hydrocarbon Emmisions Control
Catalytic Incineration without Heat Rec'y
(15% LEL)

PROP. NO.
CONT. NO.
MADE BY
APPROVED

ACCOUNT NUMBER	ITEM & DESCRIPTION	QUANTITY	UNIT	UNIT COSTS			ESTIMATED COST CENTS OMITTED			
				LABOR	SUB CONTR	MAT'L	LABOR	SUB CONTRACTS	MATERIALS	TOTAL
	Catalytic Incinerator - Capacity: 19000SCFM ~ Complete with 25 HP Blower, Controls, Interconnecting, Piping & Ductwork ~ Basis ~ Budget Quote									30,000 —
	Land (Existing)									
	Excavation & Foundations									
	Piping, Ductwork, & Insulation — Installation @ 100% Unit Cost									30,000 —
	Electrical									
	Painting									
									Sub-Total	60,000 —
	Interest on Investment During Constr (Three Months @ Prime Rate @ 6%)									900 —
									Tot. Cap. Cost	60,900 —

CODE

(E 153)

DATE ______ REVISION NO. ______ REVISION DATE ______ PAGE NO. B-23

CONSTRUCTION COST ESTIMATE

SINGMASTER & BREYER

CUSTOMER MSA Research Corp

LOCATION Evans City, Pa.

PROJECT PS-228

DESCRIPTION Hydrocarbon Emmisions Control
Catalytic Incineration without Heat Recovery
(15% LEL)

PROP. NO.
CONT. NO.
MADE BY
APPROVED

ACCOUNT NUMBER	ITEM & DESCRIPTION	QUANTITY	UNIT	UNIT COSTS			ESTIMATED COST CENTS OMITTED			
				LABOR	SUB CONTR	MAT'L	LABOR	SUB CONTRACTS	MATERIALS	TOTAL
	Catalytic Incinerator- Capacity: 20,000 SCFM ~ Complete with 50HP Blower, Controls, and Interconnecting Piping & Ductwork ~ Basis: Budget Quote and Correlation									45,000 —
	Land (Existing)									
	Excavation & Foundations Piping, Ductwork, Insulation Electrical Painting } Installation @ 100% Unit Cost									45,000 —
									Sub-Total	90,000 —
	Interest on Investment During Constr. (Three Months @ Prime Rate @ 6%)									1,350 —
									Total Cap Cost	91,350 —
									Say	91,400 —

CODE

(E 153)

DATE REVISION NO. REVISION DATE PAGE NO. B-24

CONSTRUCTION COST ESTIMATE

SINGMASTER & BREYER

CUSTOMER MSA Research Corp

LOCATION Evans City, Pa.

PROJECT PS-228

DESCRIPTION Hydrocarbon Emmisions Control
Catalytic Incineration with Primary
Heat Recovery

(15% LEL)

PROP. NO.
CONT. NO.
MADE BY
APPROVED

ACCOUNT NUMBER	ITEM & DESCRIPTION	QUANTITY	UNIT	UNIT COSTS LABOR	UNIT COSTS SUB CONTR	UNIT COSTS MAT'L	ESTIMATED COST (CENTS OMITTED) LABOR	ESTIMATED COST (CENTS OMITTED) SUB CONTRACTS	ESTIMATED COST (CENTS OMITTED) MATERIALS	ESTIMATED COST (CENTS OMITTED) TOTAL
	Catalytic Incinerator - Capacity: 1000 SCFM ~ Complete with Primary Heat Exchanger, 5 HP Blower, Controls, Interconnecting Piping & Ductwork ~ Basis: - Budget Quote & Correlation									19,500 —
	Land (Existing)									
	Excavation & Foundation Piping, Ductwork, Insulation Electrical Painting Installation @ 100% Unit Cost									19,500 —
									Sub-Total	39,000 —
	Interest on Investment During Const. (Three Months @ Prime Rate @ 6%)									600 —
									Total Cap Cost	39,600 —

CODE

(E 153)

DATE ______ REVISION NO. ______ REVISION DATE ______ PAGE NO. B-25

CONSTRUCTION COST ESTIMATE

SINGMASTER & BREYER

CUSTOMER MSA Research Corp.

LOCATION Evans City, Pa

PROJECT PS-228

DESCRIPTION Hydrocarbon Emmisions Control Catalytic Incinerator with Primary Heat Recovery

(15% LEL)

PROP. NO.

CONT. NO.

MADE BY

APPROVED

ACCOUNT NUMBER	ITEM & DESCRIPTION	QUANTITY	UNIT	UNIT COSTS LABOR	UNIT COSTS SUB CONTR	UNIT COSTS MAT'L	ESTIMATED COST (CENTS OMITTED) LABOR	ESTIMATED COST SUB CONTRACTS	ESTIMATED COST MATERIALS	ESTIMATED COST TOTAL
	Catalytic Incinerator - Capacity: 10,000 SCFM ~ Complete with Primary Heat Exchanger, 25HP Blower, Controls, Interconnection Piping & Ductwork ~ Basis: Budget Quote									60,000 —
	Land (Existing)									
	Excavation & Foundation									
	Piping, Ductwork, Insulation									60,000 —
	Electrical									
	Painting									
									Sub-Total	120,000 —
	Interest on Investment During Const. (Three Months @ Prime Rate @ 6%)									1,800 —
									Total Cap Cost	121,800 —

CODE

(E 153)

DATE ______ REVISION NO. ______ REVISION DATE ______ PAGE NO. B-26

CONSTRUCTION COST ESTIMATE

SINGMASTER & BREYER

CUSTOMER MSA Research Corp

LOCATION Evans City, Pa

PROJECT PS-228

DESCRIPTION Hydrocarbon Emmisions Control
Catalytic Incinerator with Primary
Heat Recovery
(15% LEL)

PROP. NO.

CONT. NO.

MADE BY

APPROVED

ACCOUNT NUMBER	ITEM & DESCRIPTION	QUANTITY	UNIT	UNIT COSTS			ESTIMATED COST CENTS OMITTED			
				LABOR	SUB CONTR	MAT'L	LABOR	SUB CONTRACTS	MATERIALS	TOTAL
	Catalytic Incinerator- Capacity 20,000 SCFM - Complete with Primary Heat Exchanger, 50 HP Blower, Controls, Interconnecting Piping & Ductwork ~ Basis: Budget Quote									90,000 —
	Land (Existing)									
	Excavation & Foundation									
	Piping, Ductwork, & Insulation									90,000 –
	Electrical Installation @ 100% Unit Cost									
	Painting								Sub-Total	180,000 –
	Interest on Investment During Constr. (Three Months @ Prime Rate @ 6%)									2,700 –
									Total Cap. Cost	182,700 –

CODE

(E 153)

DATE
REVISION NO.
REVISION DATE
PAGE NO. B-27

CONSTRUCTION COST ESTIMATE

SINGMASTER & BREYER

CUSTOMER MSA Research Corp

LOCATION Evans City, Pa.

PROJECT PS-228

DESCRIPTION Hydrocarbon Emmisions Control
Catalytic Incineration with Primary &
Secondary Heat Recovery
(15% LEL)

PROP. NO.
CONT. NO.
MADE BY
APPROVED

ACCOUNT NUMBER	ITEM & DESCRIPTION	QUANTITY	UNIT	UNIT COSTS			ESTIMATED COST CENTS OMITTED			
				LABOR	SUB CONTR	MAT'L	LABOR	SUB CONTRACTS	MATERIALS	TOTAL
	Catalytic Incinerator – Capacity 1000 SCFM – Complete with Primary & Secondary Heat Exchrs Two – 5HP Blowers, Controls, Interconnecting Piping & Ductwork Basis: Correlation From Budget Quote									29,900 –
	Land (Existing)									
	Excavation & Foundation									
	Piping, Ductwork, Insulation } Installation @ 100% Unit Cost									29,900 –
	Electrical									
	Painting								Sub-Total	59,800 –
	Interest on Investment During Construction (Three Months @ Prime Rate @ 6%)									900 –
									Total Cap Cost	60,700 –

CODE

(E 153)

DATE ______ REVISION NO. ______ REVISION DATE ______ PAGE NO. B-28

CONSTRUCTION COST ESTIMATE

SINGMASTER & BREYER

CUSTOMER MSA Research Corp.

LOCATION Evans City, Pa.

PROJECT PS-228

DESCRIPTION Hydrocarbon Emmisions Control
Catalytic Incineration with Primary
& Secondary Heat Recovery
(15% LEL)

PROP. NO.

CONT. NO.

MADE BY

APPROVED

ACCOUNT NUMBER	ITEM & DESCRIPTION	QUANTITY	UNIT	UNIT COSTS			ESTIMATED COST CENTS OMITTED			
				LABOR	SUB CONTR	MAT'L	LABOR	SUB CONTRACTS	MATERIALS	TOTAL
	Catalytic Incinerator - Capacity 10,000 SCFM - Complete with Primary & Secondary Heat Exchangers Two - 25 HP Blowers, Controls, Interconnecting Piping & Ductwork. Basis: Correlation from Budget Quote									97,000 –
	Land (Existing)									
	Excavation & Foundation Piping, Ductwork, Insulation Electrical Painting } Installation @ 100% Unit Cost									97,000 –
									Sub-Total	194,000 –
	Interest on Investment During Construction (Three Months @ Prime Rate @ 6%)									3,900 –
									Total Cap. Cost	196,900 –

CODE

(E 153)

DATE ____ REVISION NO. ____ REVISION DATE ____ PAGE NO. B-29

CONSTRUCTION COST ESTIMATE

SINGMASTER & BREYER

CUSTOMER MSA Research Corp

LOCATION Evans City, Pa.

PROJECT P.S.-228

DESCRIPTION Hydrocarbon Emmisions Control
Catalytic Incineration with Primary
& Secondary Heat Recovery
(15% LEL)

PROP. NO.

CONT. NO.

MADE BY

APPROVED

ACCOUNT NUMBER	ITEM & DESCRIPTION	QUANTITY	UNIT	UNIT COSTS LABOR	UNIT COSTS SUB CONTR	UNIT COSTS MAT'L	ESTIMATED COST (CENTS OMITTED) LABOR	ESTIMATED COST (CENTS OMITTED) SUB CONTRACTS	ESTIMATED COST (CENTS OMITTED) MATERIALS	ESTIMATED COST (CENTS OMITTED) TOTAL
	Catalytic Incinerator - Capacity 20,000 SCFM - Complete with Primary & Secondary Heat Exchangers, Two- 50 HP Blowers, Controls, Interconnecting Piping & Ductwork Basis: Correlation from Budget Quote									145,500 —
	Land (Existing)									
	Excavation & Foundation Piping, Ductwork, Insulation Electrical Painting } Installation @ 100% Unit Cost									145,500
									Sub-Total	291,000 —
	Interest on Investment During Const (Three Months @ Prime Rate @ 6%)									4,400 —
									Total Cap. Cost	295,400 —

CODE

(E 153)

DATE ________ REVISION NO. ________ REVISION DATE ________ PAGE NO. B-30

CONSTRUCTION COST ESTIMATE

SINGMASTER & BREYER

CUSTOMER MSA Research Corp

LOCATION Evans City, Pa.

PROJECT PS-228

DESCRIPTION Hydrocarbon Emmisions Control
Thermal Incineration without Heat Recovery
(15% LEL)

PROP. NO. ____
CONT. NO. ____
MADE BY ____
APPROVED ____

ACCOUNT NUMBER	ITEM & DESCRIPTION	QUANTITY	UNIT	UNIT COSTS			ESTIMATED COST CENTS OMITTED			
				LABOR	SUB CONTR	MAT'L	LABOR	SUB CONTRACTS	MATERIALS	TOTAL
	Thermal Incinerator* - Capacity ~ 1000 SCFM Complete with 5 HP Blower, Controls, Interconnecting Piping & Ducts Basis - Budget Quote									10,000 —
	Land (Existing)									
	Excavation & Foundations } Installation @ 100% Unit Cost									10,000 —
	Piping, Ductwork, & Insulation }									
	Electrical & Painting }								Sub-Total	20,000 —
	Interest on Investment During Constr. (Three Months @ Prime Rate - 6%)									300 —
									Total Cap Cost	20,300 —
	* Skid mounted unit; ~ 3200 lbs; $\Delta P \sim 3''$ W.C.									

CODE

(E 153)

DATE ____ REVISION NO. ____ REVISION DATE ____ PAGE NO. B-31

CONSTRUCTION COST ESTIMATE

SINGMASTER & BREYER

CUSTOMER MSA Research Corp.

LOCATION Evans City, Pa.

PROJECT PS-228

DESCRIPTION Hydrocarbon Emmisions Control
Thermal Incineration without Heat Recovery
(15% LEL)

PROP. NO.
CONT. NO.
MADE BY
APPROVED

ACCOUNT NUMBER	ITEM & DESCRIPTION	QUANTITY	UNIT	UNIT COSTS			ESTIMATED COST CENTS OMITTED			
				LABOR	SUB CONTR	MAT'L	LABOR	SUB CONTRACTS	MATERIALS	TOTAL
	Thermal Incinerator* - Capacity ~ 10,000 SCFM Complete with 25 HP Blower, Controls, Interconnecting Piping & Ducts Basis: Budget Quote									20,000 —
	Land (Existing)									
	Excavation & Foundations Piping, Ductwork, Insulation Electrical & Painting } Installation @ 100% Unit Cost									20,000 —
									Sub Total	40,000 —
	Interest on Investment During Const (Three Months @ Prime Rate - 6%)									600 —
									Total Cap. Cost.	40,600 —
	* Skid mounted unit; ~ 10,000 lbs; ΔP ~ 4-5" W.C.									

CODE

(E 153)

DATE ______ REVISION NO. ______ REVISION DATE ______ PAGE NO. B-32

CONSTRUCTION COST ESTIMATE

SINGMASTER & BREYER

CUSTOMER MSA Research Corp.

LOCATION Evans City, Pa

PROJECT PS-228

DESCRIPTION Hydrocarbon Emmisions Control
Thermal Incineration without Heat Rec'y
(15% LEL)

PROP. NO.

CONT. NO.

MADE BY

APPROVED

ACCOUNT NUMBER	ITEM & DESCRIPTION	QUANTITY	UNIT	UNIT COSTS			ESTIMATED COST CENTS OMITTED			
				LABOR	SUB CONTR	MAT'L	LABOR	SUB CONTRACTS	MATERIALS	TOTAL
	Thermal Incinerator* - Capacity ~ 20,000 SCFM ~ Complete with 50 HP Blower, Controls, Interconnecting Piping & Ducts Basis: [illegible] - Budget Quote & Correlation									25,000 -
	Land (Existing)									
	Excavation & Foundations Piping, Ductwork, Insulation Electrical Painting } Installation @ 100% Unit Cost									25,000 -
									Sub-Total	50,000 -
	Interest on Investment During Constr. (Three Months @ Prime Rate @ 6%)									750 -
									Total Cap Cost	50,750 -
									Say	5[illegible],300 -
	* skid mounted unit; ~ 14,000 lbs; ΔP ~ 4-5" W.C.									

CODE

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DATE ________ REVISION NO. ________ REVISION DATE ________ PAGE NO. B-33

CONSTRUCTION COST ESTIMATE

SINGMASTER & BREYER

CUSTOMER MSA Research Corp

LOCATION Evans City, Pa.

PROJECT PS-228

DESCRIPTION Hydrocarbon Emmisions Control
Thermal Incineration with Primary Heat Recovery
(15% LEL)

PROP. NO.
CONT. NO.
MADE BY
APPROVED

ACCOUNT NUMBER	ITEM & DESCRIPTION	QUANTITY	UNIT	UNIT COSTS			ESTIMATED COST CENTS OMITTED			
				LABOR	SUB CONTR	MAT'L	LABOR	SUB CONTRACTS	MATERIALS	TOTAL
	Thermal Incinerator - Capacity ~ 1000 SCFM ~ Complete with Primary Ht. Exchanger, 5HP Blower, Controls, Interconnecting Piping & Ducts Basis: Budget Quote & Correlation									18,500 —
	Land (Existing)									
	Excavation & Foundation Piping, Ductwork, Insulation Electrical Painting } Installation @ 100% Unit Cost									18,500 —
									Sub-Total	37,000 —
	Interest on Investment During Constr. (Three Months @ Prime Rate @ 6%)									560 —
									Total Cap Cost	37,560 —
									Say	37,600 —

CODE

(E 153)

DATE ______ REVISION NO. ______ REVISION DATE ______ PAGE NO. B-34

CONSTRUCTION COST ESTIMATE

SINGMASTER & BREYER

CUSTOMER MSA Research Corp
LOCATION Evans City, Pa
PROJECT PS-228

DESCRIPTION Hydrocarbon Emmisions Control
Thermal Incineration with Primary Heat
Recovery
(15% LEL)

PROP. NO.
CONT. NO.
MADE BY
APPROVED

ACCOUNT NUMBER	ITEM & DESCRIPTION	QUANTITY	UNIT	UNIT COSTS LABOR	UNIT COSTS SUB CONTR	UNIT COSTS MAT'L	ESTIMATED COST (CENTS OMITTED) LABOR	ESTIMATED COST SUB CONTRACTS	ESTIMATED COST MATERIALS	ESTIMATED COST TOTAL
	Thermal Incinerator – Capacity ~ 10,000 SCFM – Complete with Primary Ht. Exchanger, 25 HP Blower, Controls, Interconnecting Piping & Ducts Basis: – Budget Quote									50,000 –
	Land (Existing)									
	Excavation & Foundation Piping, Ductwork, & Insulation Electrical Painting } Installation @100% Unit Cost									50,000 –
									Sub-Total	100,000 –
	Interest on Investment During Construction (Three Months @ Prime Rate @ 6%)									1,500 –
									Total Cap. Cost	101,500 –
CODE										

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DATE ______ REVISION NO. ______ REVISION DATE ______ PAGE NO. B-35

CONSTRUCTION COST ESTIMATE

SINGMASTER & BREYER

CUSTOMER MSA Research Corp

LOCATION Evans City, Pa

PROJECT PS-228

DESCRIPTION Hydrocarbon Emissions Control ~ Thermal Incineration with Primary Heat Recovery (15% LEL)

PROP. NO. ____

CONT. NO. ____

MADE BY ____

APPROVED ____

ACCOUNT NUMBER	ITEM & DESCRIPTION	QUANTITY	UNIT	UNIT COSTS			ESTIMATED COST CENTS OMITTED			
				LABOR	SUB CONTR	MAT'L	LABOR	SUB CONTRACTS	MATERIALS	TOTAL
	Thermal Incinerator - Capacity - 20,000 SCFM - Complete with Primary Heat Exchanger, 50 HP Blower, Controls, Interconnecting Piping & Ducts ~ Basis: Budget Quote									70,000 -
	Land (Existing)									
	Excavation & Foundations } Installation @ 100% of Unit Cost									70,000 -
	Piping, Ductwork, & Insulation									
	Electrical									
	Painting									
									Sub-Total	140,000 -
	Interest on Investment During Construction (Three Months @ Prime Rate @ 6%)									2,100 -
									Total Cap. Cost	142,100 -
CODE										

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DATE ____ REVISION NO. ____ REVISION DATE ____ PAGE NO. B-36

CONSTRUCTION COST ESTIMATE

SINGMASTER & BREYER

CUSTOMER MSA Research Corp

LOCATION Evans City, Pa.

PROJECT PS-228

DESCRIPTION Hydrocarbon Emmisions Control
Thermal Incineration - with Primary &
Secondary Heat Recovery

(15% LEL)

PROP. NO.
CONT. NO.
MADE BY
APPROVED

ACCOUNT NUMBER	ITEM & DESCRIPTION	QUANTITY	UNIT	UNIT COSTS			ESTIMATED COST CENTS OMITTED			
				LABOR	SUB CONTR	MAT'L	LABOR	SUB CONTRACTS	MATERIALS	TOTAL
	Thermal Incinerator - Capacity: 1000 SCFM - Complete with Primary & Secondary Heat Exchanger, Two - 5HP Blowers, Controls, Interconnecting Piping, Ducts Basis: Corporation from Budget Quote									26,400 -
	Land (Existing)									
	Excavation & Foundations } Installation @ 100% of Unit Cost									
	Piping, Ductwork, & Insulation									26,400 -
	Electrical									
	Painting									
									Sub-Total	52,800 -
	Interest on Investment During Construction (Three Months @ Prime Rate @ 6%)									790. -
									Total Cap Cost.	53,590 -
									Say	53,600 -

CODE

(E 153)

DATE ______ REVISION NO. ______ REVISION DATE ______ PAGE NO. B-37

CONSTRUCTION COST ESTIMATE

SINGMASTER & BREYER

CUSTOMER MSA Research Corp

LOCATION Evans City, Pa

PROJECT PS- 228

DESCRIPTION Hydrocarbon Emmisions Control
Thermal Incineration- with Primary &
Secondary Heat Recovery
(15% LEL)

PROP. NO.

CONT. NO.

MADE BY

APPROVED

ACCOUNT NUMBER	ITEM & DESCRIPTION	QUANTITY	UNIT	UNIT COSTS LABOR	UNIT COSTS SUB CONTR	UNIT COSTS MAT'L	ESTIMATED COST (CENTS OMITTED) LABOR	SUB CONTRACTS	MATERIALS	TOTAL
	Thermal Incinerator- Capacity 10,000 SCFM - Complete with Primary & Secondary Heat Exchangers, Two- 25HP Blowers, Controls, Interconnecting Piping & Ducts Basis: Correlation from Budget Quote									78,000 -
	Land (Existing)									
	Excavation & Foundations Piping, Ductwork & Insulation Electrical Painting Installation @ 100% of Unit Cost									78,000 -
									Sub-Total	156,000 -
	Interest on Investment During Construction (Three Months @ Prime Rate @ 6%)									2,340 -
									Total Cap Cost	158,340 -
									Say	158,300 -

CODE

(E 153)

DATE REVISION NO. REVISION DATE PAGE NO. B-38

CONSTRUCTION COST ESTIMATE

SINGMASTER & BREYER

CUSTOMER MSA Research Corp.
LOCATION Evans City, Pa
PROJECT PS-228

DESCRIPTION Hydrocarbon Emmisions Control
Thermal Incineration with Primary & Secondary
Heat Recovery

(15% LEL)

PROP. NO.
CONT. NO.
MADE BY
APPROVED

ACCOUNT NUMBER	ITEM & DESCRIPTION	QUANTITY	UNIT	UNIT COSTS			ESTIMATED COST CENTS OMITTED			
				LABOR	SUB CONTR	MAT'L	LABOR	SUB CONTRACTS	MATERIALS	TOTAL
	Thermal Incinerator - Capacity - 20,000 SCFM - Complete with Primary & Secondary Heat Exchangers, Two 50 HP Blowers, Controls, Inter-Connecting Piping & Ducts Basis: Correlation from Budget Quote									112,500 -
	Land (Existing)									
	Excavation & Foundations Piping, Ductwork & Insulation Electrical Painting } Installation @ 100% of Unit Cost									112,500 -
									Sub-Total	225,000 -
	Interest on Investment During Construction (Three Months @ Prime Rate @ 6%)									3,400 -
									Sub-Total	228,400 -

CODE

(E 153)

DATE REVISION NO. REVISION DATE PAGE NO. 8-39

CONSTRUCTION COST ESTIMATE

SINGMASTER & BREYER

CUSTOMER MSA Research Corp
LOCATION Evans City, Pa.
PROJECT PS-228

DESCRIPTION Hydrocarbon Emmisions Control
Catalytic Incineration without Heat Recovery (25% LEL)

PROP. NO.
CONT. NO.
MADE BY
APPROVED

ACCOUNT NUMBER	ITEM & DESCRIPTION		QUANTITY	UNIT	UNIT COSTS			ESTIMATED COST CENTS OMITTED			
					LABOR	SUB CONTR	MAT'L	LABOR	SUB CONTRACTS	MATERIALS	TOTAL
	Catalytic Incinerator: Complete with Catalyst, Blower, Preheater, Controls, Interconnecting Piping & Ducts - Capacity - 1000 SCFM, HP: 3. Basis: Budget Quote										16,000 –
	Land (Existing)										
	Excavation & Foundations	Installation @ 100% of Unit Cost									
	Piping & Ductwork										16,000 –
	Insulation										
	Electrical										
	Painting									Sub-Total	32,000 –
	Interest on Investment During Construction (Thrr Months @ 6% Prime Interest Rate)										480 –
										Total Cap Cost	32,480 –
										Say	32,500 –

CODE

(E 153)

DATE ______ REVISION NO. ______ REVISION DATE ______ PAGE NO. B-40

CONSTRUCTION COST ESTIMATE

SINGMASTER & BREYER

CUSTOMER MSA Research Corp

LOCATION Evans City, Pa.

PROJECT PS-228

DESCRIPTION Hydrocarbon Emmisions Control
Catalytic Incineration without Heat Recovery
(25% LEL)

PROP. NO.

CONT. NO.

MADE BY

APPROVED

ACCOUNT NUMBER	ITEM & DESCRIPTION	QUANTITY	UNIT	UNIT COSTS			ESTIMATED COST CENTS OMITTED			
				LABOR	SUB CONTR	MAT'L	LABOR	SUB CONTRACTS	MATERIALS	TOTAL
	Catalytic Incinerator: Complete with Catalyst, Blower, Preheater, Controls, Interconnecting Piping & Ducts: Capacity 10,000 SCFM HP~25 Basis: Budget Quote									100,000 —
	Land (Existing)									
	Excavation & Foundations Installation @ 100% of Unit Cost									
	Piping & Ductwork									100,000 —
	Insulation									
	Electrical								Sub-Total	200,000 —
	Painting									3,000 —
	Interest on Investment During Construction (Three Months @ 6% Prime Rate)								Total Cap. Cost	203,000 —

CODE

(E 153)

DATE ______ REVISION NO. ______ REVISION DATE ______ PAGE NO. B-41

CONSTRUCTION COST ESTIMATE

SINGMASTER & BREYER

CUSTOMER MSA Research Corp
LOCATION Evans City, Pa
PROJECT PS-228

DESCRIPTION Hydrocarbon Emmisions Control
Catalytic Incineration without Heat Recovery (25% LEL)

PROP. NO.
CONT. NO.
MADE BY
APPROVED

ACCOUNT NUMBER	ITEM & DESCRIPTION	QUANTITY	UNIT	UNIT COSTS			ESTIMATED COST CENTS OMITTED			
				LABOR	SUB CONTR	MAT'L	LABOR	SUB CONTRACTS	MATERIALS	TOTAL
	Catalytic Incinerator: Complete with Catalyst, Booster Fan, Preheater Controls, Interconnecting Piping, & Ducts - Capacity 20,000 SCFM HP~50 Basis: Budget Quote									185,500 —
	Land (Existing)									
	Excavation & Foundations } Installation @ 100% Unit Cost									
	Piping & Ductwork									
	Insulation									
	Electrical									185,500 —
	Painting								Sub-Total	371,000 —
	Interest on Investment During Construction (Three Months @ 6% ~ Prime Rate)									5600 —
									Total Cap Cost	376,600 —

CODE

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DATE **REVISION NO.** **REVISION DATE** **PAGE NO.** B-42

CONSTRUCTION COST ESTIMATE

SINGMASTER & BREYER

CUSTOMER MSA Research Corp

LOCATION Evans City, PA

PROJECT PS-228

DESCRIPTION Hydrocarbon Emmisions Control
Catalytic Incineration with Heat Recovery
(Primary)
(25% LEL)

PROP. NO.
CONT. NO.
MADE BY
APPROVED

ACCOUNT NUMBER	ITEM & DESCRIPTION	QUANTITY	UNIT	UNIT COSTS			ESTIMATED COST CENTS OMITTED			
				LABOR	SUB CONTR	MAT'L	LABOR	SUB CONTRACTS	MATERIALS	TOTAL
	Catalytic Incinerator and Primary Heat Exchanger: Complete with Catalyst, Booster Fan :: Controls, Interconnecting Piping & Ducts - Capacity - 1000 SCFM - 5HP Basis: Budget Quote									19,900 —
	Land (Existing)									
	Excavation & Foundations									
	Piping & Ductwork									
	Insulation Installation @ 100% Unit Cost									19,900 —
	Electrical									
	Painting								SubTotal	39,800 —
	Interest on Investment During Construction (Three Months @ 6% Prime Rate)									600 —
										40,400 —

CODE

(E 153)

DATE ______ REVISION NO. ______ REVISION DATE ______ PAGE NO. B-43

CONSTRUCTION COST ESTIMATE

SINGMASTER & BREYER

CUSTOMER MSA Research Corp.

LOCATION Evans City, Pa

PROJECT PS-228

DESCRIPTION Hydrocarbon Emmisions Control
Catalytic Incineration with Heat Recovery
(Primary)
(25% LEL)

PROP. NO.
CONT. NO.
MADE BY
APPROVED

ACCOUNT NUMBER	ITEM & DESCRIPTION	QUANTITY	UNIT	UNIT COSTS			ESTIMATED COST CENTS OMITTED			
				LABOR	SUB CONTR	MAT'L	LABOR	SUB CONTRACTS	MATERIALS	TOTAL
	Catalytic Incinerator and Primary Heat Exchanger: Complete with Catalyst, Booster Fan, Controls, Interconnecting Piping & Ducts - Capacity - 10,000 SCFM 50HP ~ Basis: Budget Quote . . . :									112,500 —
	Land (Existing)									
	Excavation & Foundations Piping & Ductwork Insulation Electrical Painting Installation @ 100% Unit Cost									112,500 —
									Sub Total	225,000 —
	Interest on Investment During Construction (Three Months @ 6% Prime Rate)									3,400 —
									Total Cap Cost	228,400 —

CODE

(E 153)

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CONSTRUCTION COST ESTIMATE

SINGMASTER & BREYER

CUSTOMER MSA Research Corp
LOCATION Evans City, Pa.
PROJECT PS-228

DESCRIPTION Hydrocarbon Emmisions Control
Catalytic Incineration with Heat Recovery
(Primary)
(25% LEL)

PROP. NO.
CONT. NO.
MADE BY
APPROVED

ACCOUNT NUMBER	ITEM & DESCRIPTION	QUANTITY	UNIT	UNIT COSTS			ESTIMATED COST CENTS OMITTED			
				LABOR	SUB CONTR	MAT'L	LABOR	SUB CONTRACTS	MATERIALS	TOTAL
	Catalytic Incinerator and Primary Heat Exchanger: Complete with Catalyst, Booster Fan, Controls, Interconnecting Piping & Ducts - Capacity - 20,000 SCFM HP≈100 Basis: Budget Quote									211,000 —
	Land (Existing)									
	Excavation & Foundations Piping & Ductwork Insulation Electrical Painting Installation @100% Unit Cost									211,000 —
									Sub Total	422,000 —
	Interest on Investment During Construction (Three Months @6% - Prime Rate)									6,330 —
									Total Cap Cost	428,330 —
									Say	428,300 —

CODE

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CONSTRUCTION COST ESTIMATE

SINGMASTER & BREYER

CUSTOMER MSA Research Corp

LOCATION Evans City, Pa.

PROJECT PS-228

DESCRIPTION Hydrocarbon Emmisions Control

Catalytic Incineration with Primary & Secondary Heat Recovery (25% LEL)

PROP. NO.

CONT. NO.

MADE BY

APPROVED

ACCOUNT NUMBER	ITEM & DESCRIPTION	QUANTITY	UNIT	UNIT COSTS			ESTIMATED COST CENTS OMITTED			
				LABOR	SUB CONTR	MAT'L	LABOR	SUB CONTRACTS	MATERIALS	TOTAL
	Catalytic Incinerator, Primary & Secondary Heat Exchangers, Booster & Make-Up Fans, Catalyst, Controls, Interconnecting Piping & Ducts - Capacity 1000 SCFM HP~ 12 Basis~ Budget Quote.									25,100 —
	Land (Existing)									
	Excavation & Foundations Piping, Ductwork, & Insulation Electrical Painting } Installation @ 100% Unit Cost									25,100 —
									Sub Total	50,200 —
	Interest on Investment During Construction (Three Months @ 6% Prime Rate)									750 —
									Total Cap Cost	50,950 —
									Say	51,000 —

CODE

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DATE ______ REVISION NO. ______ REVISION DATE ______ PAGE NO. 8-46

CONSTRUCTION COST ESTIMATE.

SINGMASTER & BREYER

CUSTOMER MSA Research Corp

LOCATION Evans City, Pa

PROJECT PS-228

DESCRIPTION Hydrocarbon Emmisions Control

Catalytic Incineration with Primary and Secondary Heat Recovery (25% LEL)

PROP. NO.

CONT. NO.

MADE BY

APPROVED

ACCOUNT NUMBER	ITEM & DESCRIPTION	QUANTITY	UNIT	UNIT COSTS			ESTIMATED COST CENTS OMITTED			
				LABOR	SUB CONTR	MAT'L	LABOR	SUB CONTRACTS	MATERIALS	TOTAL
	Catalytic Incinerator, Primary & Secondary Heat Exchangers, Booster & Make-Up Fans, Catalyst, Controls, Inter-connecting Piping & Ducts - Capacity ~ 10,000 scfm, HP ~ 100, Basis: Budget Quote and Correlation									133,000 –
	Land (Existing)									
	Excavation & Foundations Piping, Ductwork, & Insulation Electrical Painting } Installation @ 100% Unit Cost									133,000 –
									Sub-Total	266,000 –
	Interest on Investment During Construction (Three Months @ 6% Prime Rate)									3,990 –
									Total Cap Cost	269,990 –
									Say	270,000 –

CODE

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CONSTRUCTION COST ESTIMATE

SINGMASTER & BREYER

CUSTOMER MSA Research Corp

LOCATION Evans City, Pa.

PROJECT PS-228

DESCRIPTION Hydrocarbon Emmisions Control

Catalytic Incineration with Primary & Secondary Heat Recovery (25% LEL)

PROP. NO.

CONT. NO.

MADE BY

APPROVED

ACCOUNT NUMBER	ITEM & DESCRIPTION	QUANTITY	UNIT	UNIT COSTS			ESTIMATED COST CENTS OMITTED			
				LABOR	SUB CONTR	MAT'L	LABOR	SUB CONTRACTS	MATERIALS	TOTAL
	Catalytic Incinerator, Primary & Secondary Heat Exchangers, Booster & Make-Up Fans, Catalyst, Controls, Interconnecting Piping & Ducts - Capacity: 20,000 SCFM, HP: 200 Basis: Budget Quote & Correlation									245,000 —
	Land (Existing)									
	Excavation & Foundations Piping, Ductwork, & Insulation Electrical Painting } Installation @ 100% Unit Cost									245,000 —
									Sub-Total	490,000 —
	Interest On Investment During Construction (Three Months @ 6% Prime Rate)									7,350 —
									Total Cap Cost	497,350 —
									Say	497,400 —

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DATE ______ REVISION NO. ______ REVISION DATE ______ PAGE NO. B-48

CONSTRUCTION COST ESTIMATE

SINGMASTER & BREYER

CUSTOMER MSA Research Corp
LOCATION Evans City, PA
PROJECT PS-228

DESCRIPTION Hydrocarbon Emissions Control via Incineration -
Thermal Incineration without Heat Recovery (25% LEL)

PROP. NO.
CONT. NO.
MADE BY
APPROVED

ACCOUNT NUMBER	ITEM & DESCRIPTION		QUANTITY	UNIT	UNIT COSTS			ESTIMATED COST CENTS OMITTED			
					LABOR	SUB CONTR	MAT'L	LABOR	SUB CONTRACTS	MATERIALS	TOTAL
	Thermal Incinerator: Complete with 3 HP Booster Fan , Controls, Interconnecting Piping, and Ducts Capacity - 1000 SCFM - Basis: Budget, Verbal & Written Quotes										10,000 —
	Land - (Existing)										
	Excavation & Foundations	Installation @ 100% of unit cost									10,000 —
	Piping & Ductwork										
	Insulation										
	Electrical										
	Painting										
										Sub-Total	20,000. —
	Interest on Investment During Construction (Three Months @ Prime Rate @ 6%)										300 —
CODE										Total Capital Cost	20,300 —

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CONSTRUCTION COST ESTIMATE

SINGMASTER & BREYER

CUSTOMER MSA Research Corp

LOCATION Evans City, Pa.

PROJECT PS-228

DESCRIPTION Hydrocarbon Emmisions Control via Incineration

Thermal Incineration without Heat Recovery (25% LEL)

PROP. NO.

CONT. NO.

MADE BY

APPROVED

ACCOUNT NUMBER	ITEM & DESCRIPTION	QUANTITY	UNIT	UNIT COSTS LABOR	UNIT COSTS SUB CONTR	UNIT COSTS MAT'L	ESTIMATED COST (CENTS OMITTED) LABOR	ESTIMATED COST (CENTS OMITTED) SUB CONTRACTS	ESTIMATED COST (CENTS OMITTED) MATERIALS	ESTIMATED COST (CENTS OMITTED) TOTAL
	Thermal Incinerator: Complete with 25HP Booster Fan, Controls, Interconnecting piping, and ducts Capacity: 10,000 SCFM - Basis: Budget Verbal & Writen Quotes									34,000 —
	Land - (Existing)									
	Excavation & Foundations									
	Piping & Ductwork Installation @ 100 % of unit cost									34,000 —
	Insulation									
	Electrical									
	Painting								Sub-Total	68,000 -
	Interest on Investment During Construction (Three Months @ Prime Interest Rate @ 6%)									1,000 -
									Total Capital Cost	69,000 —

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DATE ______ REVISION NO. ______ REVISION DATE ______ PAGE NO. B-50

CONSTRUCTION COST ESTIMATE

SINGMASTER & BREYER

CUSTOMER MSA RESEARCH CORP

LOCATION EVANS CITY, PA.

PROJECT PS-228

DESCRIPTION HYDROCARBON EMMISIONS CONTROL
VIA INCINERATION

THERMAL INCINERATION WITHOUT HEAT RECOVERY
(25% LEL)

PROP. NO.
CONT. NO.
MADE BY
APPROVED

ACCOUNT NUMBER	ITEM & DESCRIPTION	QUANTITY	UNIT	UNIT COSTS			ESTIMATED COST CENTS OMITTED			
				LABOR	SUB CONTR	MAT'L	LABOR	SUB CONTRACTS	MATERIALS	TOTAL
	THERMAL INCINERATOR: COMPLETE WITH 50 HP BOOSTER FAN, CONTROLS; INTERCONNECTING PIPING & DUCTS CAPACITY: 20,000± SCFM-BASIS: BUDGET VERBAL & WRITTEN QUOTES									50,500 —
	LAND (EXISTING)									
	EXCAVATION & FOUNDATIONS PIPING & DUCTWORK INSULATION ELECTRICAL PAINTING INSTALLATION @ 100% OF UNIT COST									50,500 —
									SUB-TOTAL	101,000 —
	INTEREST ON INVESTMENT DURING CONSTRUCTION (THREE MONTHS @ PRIME INTEREST RATE @ 6%)									1,500 —
									TOTAL CAPITAL COST	102,500 —

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DATE ______ REVISION NO. ______ REVISION DATE ______ PAGE NO. B-51

CONSTRUCTION COST ESTIMATE

SINGMASTER & BREYER

CUSTOMER MSA RESEARCH CORP.

LOCATION EVANS CITY, PA.

PROJECT PS-228

DESCRIPTION HYDROCARBON EMMISIONS CONTROL
VIA INCINERATION

THERMAL INCINERATION WITH HEAT RECOVERY
(25% LEL) (PRIMARY)

PROP. NO.

CONT. NO.

MADE BY

APPROVED

ACCOUNT NUMBER	ITEM & DESCRIPTION	QUANTITY	UNIT	UNIT COSTS			ESTIMATED COST CENTS OMITTED			
				LABOR	SUB CONTR	MAT'L	LABOR	SUB CONTRACTS	MATERIALS	TOTAL
	THERMAL INCINERATOR & *PRIMARY HEAT EXCHANGER: COMPLETE WITH 5HP BOOSTER FAN, CONTROLS, INTERCONNECTING PIPING & DUCTS CAPACITY: 1000 SCFM - BASIS: BUDGET VERBAL & WRITTEN QUOTES									14,800 —
	LAND (EXISTING)									
	EXCAVATION & FOUNDATIONS									
	PIPING & DUCTWORK									
	INSULATION INSTALLATION @ 100% OF UNIT COST									14,800 —
	ELECTRICAL									
	PAINTING									
									SUB-TOTAL	29,600 —
	INTEREST ON INVESTMENT DURING CONSTRUCTION (THREE MONTHS @ PRIME INTEREST RATE @ 6%									450 —
	*HEAT EXCHANGER - $4400 ADDITIONAL COST IS AN ESTIMATE									
CODE									TOTAL CAPITAL COST	30,050 —
									SAY	30,100 —

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CONSTRUCTION COST ESTIMATE

SINGMASTER & BREYER

CUSTOMER MSA RESEARCH CORP.

LOCATION EVANS CITY, PA

PROJECT PS-228

DESCRIPTION HYDROCARBON EMMISIONS CONTROL VIA INCINERATION

THERMAL INCINERATION WITH HEAT RECOVERY (25% LEL) (PRIMARY)

PROP. NO.

CONT. NO.

MADE BY

APPROVED

ACCOUNT NUMBER	ITEM & DESCRIPTION	QUANTITY	UNIT	UNIT COSTS LABOR	UNIT COSTS SUB CONTR	UNIT COSTS MAT'L	ESTIMATED COST (CENTS OMITTED) LABOR	ESTIMATED COST SUB CONTRACTS	ESTIMATED COST MATERIALS	ESTIMATED COST TOTAL
	THERMAL INCINERATOR & PRIMARY HEAT EXCHANGER: COMPLETE WITH 50HP BOOSTER FAN, CONTROLS, INTERCONNECTING PIPING & DUCTS CAPACITY - 10,000 SCFM - BASIS - BUDGET VERBAL & WRITTEN QUOTES									53,000 —
	LAND (EXISTING)									
	EXCAVATION & FOUNDATIONS PIPING & DUCTWORK INSULATION ELECTRICAL PAINTING INSTALLATION @ 100% OF UNIT COST									53,000 —
									SUB TOTAL	106,000 —
	INTEREST ON INVESTMENT DURING CONSTRUCTION (THREE MONTHS @ PRIME INTEREST RATE @ 6%)									1,600 —
									TOTAL CAPITAL COST	107,600 —

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CONSTRUCTION COST ESTIMATE

SINGMASTER & BREYER

CUSTOMER MSA Research Corp
LOCATION Evans City, PA
PROJECT PS-228

DESCRIPTION Hydrocarbon Emmisions Control
via Incineration

Thermal Incineration with Heat Recovery
(25% LEL) (Primary)

PROP. NO.
CONT. NO.
MADE BY
APPROVED

ACCOUNT NUMBER	ITEM & DESCRIPTION	QUANTITY	UNIT	UNIT COSTS LABOR	UNIT COSTS SUB CONTR	UNIT COSTS MAT'L	ESTIMATED COST (CENTS OMITTED) LABOR	ESTIMATED COST (CENTS OMITTED) SUB CONTRACTS	ESTIMATED COST (CENTS OMITTED) MATERIALS	ESTIMATED COST (CENTS OMITTED) TOTAL
	Thermal Incinerator & Primary Heat Exchanger: Complete with 100 HP Booster Fan, Controls, Interconnecting Piping & Ducts Capacity - 20,000 SCFM Basis: Budget Verbal & Written Quotes									85,500 —
	Land (Existing)									
	Excavation & Foundations Piping & Ductwork Insulation Electrical Painting Installation @ 100% of unit cost									85,500 —
									Sub-Total	171,000 —
	Interest on Investment During Construction (Three Months @ Prime Interest Rate @ 6%)									2,600 —
									Total Capital Cost	173,600 —

CODE

(E 153)

DATE
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CONSTRUCTION COST ESTIMATE

SINGMASTER & BREYER

CUSTOMER MSA Research Corp

LOCATION Evans City, Pa

PROJECT PS-228

DESCRIPTION Hydrocarbon Emmisions Control via Incineration

Thermal Incineration with Primary & Secondary Heat Recovery (25% LEL)

PROP. NO.

CONT. NO.

MADE BY

APPROVED

ACCOUNT NUMBER	ITEM & DESCRIPTION	QUANTITY	UNIT	UNIT COSTS LABOR	UNIT COSTS SUB CONTR	UNIT COSTS MAT'L	ESTIMATED COST (CENTS OMITTED) LABOR	ESTIMATED COST SUB CONTRACTS	ESTIMATED COST MATERIALS	ESTIMATED COST TOTAL
	Thermal Incinerator & *Primary Heat Exchanger: With Booster Fan, Controls, Piping & Ducts - Capacity: 1000 SCFM - Basis: Budget Verbal & Written Quotes (5 HP)									14,800 —
	Secondary *Heat Exchanger & Make-up Air Fan - Capacity: 1000 SCFM - Basis: Budget Verbal & Written Quotes (5 HP)									5,200 —
	Land - (Existing) Excavation & Foundations Piping, Ductwork, & Insulation Electrical Painting } Installation @ 100% of Unit Cost									20,000 —
									Sub-Total	40,000 —
	Interest on Investment During Construction (Three Months @ Prime Interest Rate @ 6%)									600 —
	*Heat Exchangers - $ 4400 additional for Primary and $ 3800 additional for Secondary units are estimates cost data in Quotes									
CODE									Total Capital Cost	40,600 —

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CONSTRUCTION COST ESTIMATE

SINGMASTER & BREYER

CUSTOMER MSA Research Corp

LOCATION Evans City, Pa.

PROJECT PS-228

DESCRIPTION Hydrocarbons Emmisions Control via Incineration -

Thermal Incineration with Primary and Secondary Heat Recovery (25% LEL)

PROP. NO.

CONT. NO.

MADE BY

APPROVED

ACCOUNT NUMBER	ITEM & DESCRIPTION	QUANTITY	UNIT	UNIT COSTS			ESTIMATED COST CENTS OMITTED			
				LABOR	SUB CONTR	MAT'L	LABOR	SUB CONTRACTS	MATERIALS	TOTAL
	Thermal Incinerator & Primary Heat Exchanger with Booster Fan, Controls, Piping & Ducts - Capacity; 10,000 SCFM - Basis: Budget Verbal & Written Quotes (50HP)									53,000 —
	Secondary* Heat Exchanger & Make-Up AirFan - Capacity: 10,000 SCFM - Basis Budget Verbal & Written Quotes (50HP)									20,500 —
	Land (Existing) Excavation & Foundations Piping, Ductwork, & Insulation Electrical Painting } Installation @ 100% of Unit Cost									73,500 —
									Sub-Total	147,000 —
	Interest on Investment During Construction (Three Months at Prime Interest Rate @ 6%)									2,200 —
	*Cost is estimated from price data in Quotes									
CODE									Total Capital Cost	149,200 —

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CONSTRUCTION COST ESTIMATE

SINGMASTER & BREYER

CUSTOMER MSA Research Corp

LOCATION Evans City, Pa

PROJECT PS-228

DESCRIPTION Hydrocarbon Emmisions Control
Via Incineration -

Thermal Incineration with Primary & Secondary Heat Recovery (25% LEL)

PROP. NO.

CONT. NO.

MADE BY

APPROVED

ACCOUNT NUMBER	ITEM & DESCRIPTION	QUANTITY	UNIT	UNIT COSTS			ESTIMATED COST CENTS OMITTED			
				LABOR	SUB CONTR	MAT'L	LABOR	SUB CONTRACTS	MATERIALS	TOTAL
	Thermal Incinerator & Primary Heat Exchanger with Booster Fan, Controls, Piping & Ducts - Capacity: 20,000 SCFM - Basis: Budget & Verbal Written Quotes (100HP)									85,500 —
	Secondary* Heat Exchanger & Make-Up Air Fan - Capacity: 20,000 SCFM - Basis: Budget Verbal & Written Quotes (100HP									33,000 —
	Land (Existing) Excavation & Foundations Piping, Ductwork, & Insulation Electrical Painting } Installation @ 100% of Unit Cost									118,500 —
									Sub-Total	237,000 —
	Interest on Investment During Construction (Three Months at Prime Interest Rate @ 6%)									3,600 —
	*Cost is estimated from price data in Quotes									
									Total Capital Cost	240,600 —

CODE

(E 153)

DATE ______ REVISION NO. ______ REVISION DATE ______ PAGE NO. B-57

MANUFACTURING ESTIMATE - OVEN EXHAUST CONTROL SCHEME

CONTROL PROCESS: CATALYTIC INCINERATION w/o HEAT RECOVERY ~ OVEN EXHAUST RATE ~ 1000 SCFM (15% LEL)

PROCESS OPERATING TIME: 2 SHIFTS/DAY 365 DAYS/YR 5840 HR/YR

ITEM	DESCRIPTION	COST $/YR	COST ¢/M SCF
RAW MATERIALS			
UTILITIES:			
COOLING WATER	$.03/$10^3$ GAL.		
STEAM	$1.00/$10^3$ LB		
NATURAL GAS	$.60/$10^6$ Btu × .350×10^6 Btu/HR × 5840 HR/YR	1230	
ELECTRICITY	$.015/KWH × 5 HP × .746 KW/HP × 5840 HR/YR	327	
MAINTENANCE:			
GENERAL MAINT.	5% CAPITAL COST (22,000)	1100	
MAINT. SUPPLIES	CATALYST	390	
DIRECT LABOR:	.5 HR/SHIFT × 730 SHIFT/YR × $4/HR	1460	
SUPERVISION:	10% DIRECT LABOR	146	
DIRECT MFG. COST		4653	
PAYROLL OVERHEAD	30% DIRECT LABOR	438	
PLANT OVERHEAD:	50% DIRECT LABOR	730	
PACKAGING:		–	
SHIPPING:		–	
INDIRECT MFG. COST		1168	
DEPRECIATION:	10% CAPITAL COST (22,330)	2233	
PROPERTY TAXES:	1% CAPITAL COST (22,330)	223	
INSURANCE:	0.5% CAPITAL COST (22,000)	110	
FIXED MFG COST		2566	
TOTAL PLANT LEVEL COST		8387	
CORPORATE OVERHEAD	3% TOTAL PLANT LEVEL COST	252	
TOTAL MFG COST		8639	
	SAY	8600	.0241

MANUFACTURING ESTIMATE - OVEN EXHAUST CONTROL SCHEME

CONTROL PROCESS: CATALYTIC INCINERATION w/o HEAT RECOVERY ON OVEN EXHAUST RATE 10,000 SCFM (15% LEL)

PROCESS OPERATING TIME: 2 SHIFTS/DAY 365 DAYS/YR 5840 HR/YR

ITEM	DESCRIPTION	COST	
		$/YR	$/M SCF
RAW MATERIALS			
UTILITIES:			
COOLING WATER	$.03/$10^3$ GAL.		
STEAM	$1.00/$10^3$ LB		
NATURAL GAS	$.60/$10^6$ Btu × 3.5 × 10^6 Btu/HR × 5840 HR/YR	12,300	
ELECTRICITY	$.015/KWH × 25 HP × .746 KW/HP × 5840 HR/YR	1,635	
MAINTENANCE:			
GENERAL MAINT.	5% CAPITAL COST (60,000)	3,000	
MAINT. SUPPLIES	CATALYST	3,900	
DIRECT LABOR:	.5 HR/SHIFT × 730 SHIFT/YR × $4/HR	1,460	
SUPERVISION:	10% DIRECT LABOR	146	
DIRECT MFG. COST		22,441	
PAYROLL OVERHEAD:	30% DIRECT LABOR	438	
PLANT OVERHEAD:	50% DIRECT LABOR	730	
PACKAGING:		—	
SHIPPING:		—	
INDIRECT MFG. COST		1168	
DEPRECIATION:	10% CAPITAL COST (60,900)	6090	
PROPERTY TAXES:	1% CAPITAL COST (60,900)	609	
INSURANCE:	0.5% CAPITAL COST (60,000)	300	
FIXED MFG COST		6999	
TOTAL PLANT LEVEL COST		30,608	
CORPORATE OVERHEAD	3% TOTAL PLANT LEVEL COST	918	
TOTAL - MFG COST		31,526	
	SAY	31,500	.009

MANUFACTURING ESTIMATE - OVEN EXHAUST CONTROL SCHEME

CONTROL PROCESS: CATALYTIC INCINERATION w/o HEAT RECOVERY ~ OVEN EXHAUST RATE ~ 20,000 SCFM (15% LEL)

PROCESS OPERATING TIME: 2 SHIFTS/DAY 365 DAYS/YR 5840 HR/YR

ITEM	DESCRIPTION	COST $/YR	COST $/M SCF
RAW MATERIALS			
UTILITIES:			
COOLING WATER	$.03/$10^3$ GAL.		
STEAM	$1.00/$10^3$ LB		
NATURAL GAS	$.60/$10^6$ Btu × 7×10^6 Btu/HR × 5840 HR/YR	24600	
ELECTRICITY	$.015/KWH × 50 HP × .746 KW/HP × 5840 HR/YR	3270	
MAINTENANCE:			
GENERAL MAINT.	5% CAPITAL COST (90000)	4500	
MAINT. SUPPLIES	CATALYST	7800	
DIRECT LABOR:	.5 HR/SHIFT × 730 SHIFT/YR × $4/HR	1460	
SUPERVISION:	10% DIRECT LABOR	146	
DIRECT MFG. COST		41776	
PAYROLL OVERHEAD:	30% DIRECT LABOR	438	
PLANT OVERHEAD:	50% DIRECT LABOR	730	
PACKAGING:		-	
SHIPPING:		-	
INDIRECT MFG. COST		1168	
DEPRECIATION:	10% CAPITAL COST (91,350)	9135	
PROPERTY TAXES:	1% CAPITAL COST (91350)	914	
INSURANCE:	0.5% CAPITAL COST (90000)	450	
FIXED MFG COST		10,499	
TOTAL PLANT LEVEL COST		53,443	
CORPORATE OVERHEAD	3% TOTAL PLANT LEVEL COST	1603	
TOTAL MFG COST		55,046	
	SAY	55,000	.0079

MANUFACTURING ESTIMATE - OVEN EXHAUST CONTROL SCHEME

CONTROL PROCESS: CATALYTIC INCINERATION W/PRIMARY HEAT RECOVERY - OVEN EXHAUST

PROCESS OPERATING TIME: 2 SHIFTS/DAY 365 DAYS/YR 5840 HR/YR RATE ≈ 1000 SCFM (15% LEL)

ITEM	DESCRIPTION	COST $/YR	COST $/M SCF
RAW MATERIALS			
UTILITIES:			
COOLING WATER	$ .03/10^3 GAL.		
STEAM	$ 1.00/10^3 LB		
NATURAL GAS	$ .60/10^6 Btu × .0178 × 10^6 Btu/HR × 5840 HR/YR	62	
ELECTRICITY	$ .015/KWH × 5HP × .746KW/HP × 5840 HR/YR	327	
MAINTENANCE:			
GENERAL MAINT.	5% CAPITAL COST (39000)	1950	
MAINT. SUPPLIES	CATALYST	392	
DIRECT LABOR:	.5 HR/SHIFT × 730 SHIFT/YR × $ 4/HR	1460	
SUPERVISION:	10% DIRECT LABOR	146	
DIRECT MFG. COST		4335	
PAYROLL OVERHEAD:	30% DIRECT LABOR	438	
PLANT OVERHEAD:	50% DIRECT LABOR	730	
PACKAGING:		-	
SHIPPING:		-	
INDIRECT MFG. COST		1168	
DEPRECIATION:	10% CAPITAL COST (39,600)	3960	
PROPERTY TAXES:	1% CAPITAL COST (39,600)	396	
INSURANCE:	0.5% CAPITAL COST (39,000)	195	
FIXED MFG COST		4551	
TOTAL PLANT LEVEL COST		10,054	
CORPORATE OVERHEAD	3% TOTAL PLANT LEVEL COST	301	
TOTAL MFG COST		10355	
	SAY	10,400	.0296

MANUFACTURING ESTIMATE - OVEN EXHAUST CONTROL SCHEME

CONTROL PROCESS: CATALYTIC INCINERATION w/PRIMARY HEAT RECOVERY ~ OVEN EXHAUST RATE ~ 10,000 SCFM (15% LEL)

PROCESS OPERATING TIME: 2 SHIFTS/DAY 365 DAYS/YR 5840 HR/YR

ITEM	DESCRIPTION	COST $/YR	COST $/M SCF
RAW MATERIALS			
UTILITIES:			
COOLING WATER	$.03/$10^3$ GAL.		
STEAM	$1.00/$10^3$ LB		
NATURAL GAS	$.60/$10^6$ Btu × .178×10^6 Btu/Hr × 5840 Hr/Yr	620	
ELECTRICITY	$.015/KWH × 25 HP × .746 KW/HP × 5840 Hr/Yr	1635	
MAINTENANCE:			
GENERAL MAINT.	5% CAPITAL COST (120,000)	6000	
MAINT. SUPPLIES	CATALYST	3900	
DIRECT LABOR:	.5 Hr/SHIFT × 730 SHIFT/YR × $4./Hr	1460	
SUPERVISION:	10% DIRECT LABOR	146	
DIRECT MFG. COST		13761	
PAYROLL OVERHEAD:	30% DIRECT LABOR	438	
PLANT OVERHEAD:	50% DIRECT LABOR	730	
PACKAGING:		-	
SHIPPING:		-	
INDIRECT MFG. COST		1168	
DEPRECIATION:	10% CAPITAL COST (121,800)	12,180	
PROPERTY TAXES:	1% CAPITAL COST (121,800)	1,218	
INSURANCE:	0.5% CAPITAL COST (120,000)	600	
FIXED MFG COST		13,998	
TOTAL PLANT LEVEL COST		28927	
CORPORATE OVERHEAD	3% TOTAL PLANT LEVEL COST	868	
TOTAL-MFG COST		29795	
	SAY	29,800	.0085

B-62

MANUFACTURING ESTIMATE - OVEN EXHAUST CONTROL SCHEME

CONTROL PROCESS: CATALYTIC INCINERATION W/PRIMARY HEAT RECOVERY ~ OVEN EXHAUST

PROCESS OPERATING TIME: 2 SHIFTS/DAY 365 DAYS/YR 5840 HR/YR RATE ~ 20,000 SCFM (15% LEL)

ITEM	DESCRIPTION	COST $/YR	COST $/M SCF
RAW MATERIALS			
UTILITIES:			
COOLING WATER	$.03/10³ GAL.		
STEAM	$1.00/10³ LB		
NATURAL GAS	$.60/10⁶ Btu × .356 Btu/Hr × 5840 Hr/Yr	1240	
ELECTRICITY	$.015/KWH × 50 HP × .746 KW/HP × 5840 HR/YR	3270	
MAINTENANCE:			
GENERAL MAINT.	5% CAPITAL COST (180,000)	9000	
MAINT. SUPPLIES	CATALYST	7800	
DIRECT LABOR:	.5 HR/SHIFT × 730 SHIFT/YR × $4./HR	1460	
SUPERVISION:	10% DIRECT LABOR	146	
DIRECT MFG. COST		22,916	
PAYROLL OVERHEAD	30% DIRECT LABOR	438	
PLANT OVERHEAD:	50% DIRECT LABOR	730	
PACKAGING:			
SHIPPING:			
INDIRECT MFG. COST		1168	
DEPRECIATION:	10% CAPITAL COST (182,700)	18,270	
PROPERTY TAXES:	1% CAPITAL COST (182,700)	1827	
INSURANCE:	0.5% CAPITAL COST (180,000)	900	
FIXED MFG COST		20,997	
TOTAL PLANT LEVEL COST		45,081	
CORPORATE OVERHEAD	3% TOTAL PLANT LEVEL COST	1,352	
TOTAL - MFG COST		46,433	
	SAY	46,450	.0066

MANUFACTURING ESTIMATE - OVEN EXHAUST CONTROL SCHEME

CONTROL PROCESS: CATALYTIC INCINERATION w/PRIMARY & SECONDARY HEAT RECOVERY ~ OVEN EXHAUST RATE ~ 1000 SCFM (15% LEL)

PROCESS OPERATING TIME: 2 SHIFTS/DAY 365 DAYS/YR 5840 HR/YR

ITEM	DESCRIPTION	COST $/YR	COST $/M SCF
RAW MATERIALS			
UTILITIES:			
COOLING WATER	$.03/$10^3$ GAL.		
STEAM	$1.00/$10^3$ LB		
NATURAL GAS	$.60/$10^6$ Btu x .0178 x 10^6 Btu/HR x 5840 HR/YR	62	
ELECTRICITY	$.015/KWH x 10 HP x .746 KW/HP x 5840 HR/YR	654	
MAINTENANCE:			
GENERAL MAINT.	5% CAPITAL COST (59,800)	2990	
MAINT. SUPPLIES	CATALYST	390	
DIRECT LABOR:	.5 HR/SHIFT x 730 SHIFT/YR x $4/HR	1460	
SUPERVISION:	10% DIRECT LABOR	146	
DIRECT MFG. COST		5702	
PAYROLL OVERHEAD	30% DIRECT LABOR	438	
PLANT OVERHEAD:	50% DIRECT LABOR	730	
PACKAGING:		-	
SHIPPING:		-	
INDIRECT MFG. COST		1168	
DEPRECIATION:	10% CAPITAL COST (60,700)	6070	
PROPERTY TAXES:	1% CAPITAL COST (60,700)	607	
INSURANCE:	0.5% CAPITAL COST (59,800)	299	
FIXED MFG COST		6976	
TOTAL PLANT LEVEL COST		13,846	
CORPORATE OVERHEAD	3% TOTAL PLANT LEVEL COST	415	
TOTAL-MFG COST		14,261	
	FUEL SAVINGS LESS SAVINGS	1295	
	$.60/$10^6$ Btu x .368 x 10^6 Btu/HR x 5840 HR/YR = 1295	12966	
		13,000	.0372

MANUFACTURING ESTIMATE - OVEN EXHAUST CONTROL SCHEME

CONTROL PROCESS: CATALYTIC INCINERATION w/PRIMARY & SECONDARY HT RECOVERY ~ OVEN EXHAUST RATE ~ 10,000 SCFM (15% LEL)

PROCESS OPERATING TIME: 2 SHIFTS/DAY 365 DAYS/YR 5840 HR/YR

ITEM	DESCRIPTION	COST	
		$/YR	$/MSCF
RAW MATERIALS			
UTILITIES:			
COOLING WATER	$.03/10³ GAL.		
STEAM	$1.00/10³ LB		
NATURAL GAS	$.60/10⁶ Btu × .178×10⁶ Btu/HR × 5840 HR/YR	620	
ELECTRICITY	$.015/KWH × 50HP × .746 KW/HP × 5840 HR/YR	3270	
MAINTENANCE:			
GENERAL MAINT.	5% CAPITAL COST (194,000)	9700	
MAINT. SUPPLIES	CATALYST	3900	
DIRECT LABOR:	.5 HR/SHIFT × 730 SHIFT/YR × $4/HR	1460	
SUPERVISION:	10% DIRECT LABOR	146	
DIRECT MFG. COST		19,096	
PAYROLL OVERHEAD	30% DIRECT LABOR	438	
PLANT OVERHEAD:	50% DIRECT LABOR	730	
PACKAGING:		-	
SHIPPING:		-	
INDIRECT MFG. COST		1168	
DEPRECIATION:	10% CAPITAL COST (196,900)	19690	
PROPERTY TAXES:	1% CAPITAL COST (196,900)	1969	
INSURANCE:	0.5% CAPITAL COST (194,000)	970	
FIXED MFG COST		22629	
TOTAL PLANT LEVEL COST		42,893	
CORPORATE OVERHEAD	3% TOTAL PLANT LEVEL COST	1,287	
TOTAL-MFG COST		44,180	
	FUEL SAVINGS: 3.68 ×10⁶ Btu/HR × $.60/10⁶ Btu × 5840 HR/YR = 12950 LESS SAVINGS	12,950	
		31,230	
	SAY	31,200	.009

8-65

MANUFACTURING ESTIMATE - OVEN EXHAUST CONTROL SCHEME

CONTROL PROCESS: CATALYTIC INCINERATION w/ PRIMARY & SECONDARY HEAT RECOVERY IN OVEN

PROCESS OPERATING TIME: 2 SHIFTS/DAY 365 DAYS/YR 5840 HR/YR EXHAUST RATE 20,000 SCFM (15% LEL)

ITEM	DESCRIPTION	COST $/YR	COST $/M SCF
RAW MATERIALS			
UTILITIES:			
COOLING WATER	$.03/$10^3$ GAL.		
STEAM	$1.00/$10^3$ LB		
NATURAL GAS	$ .60/10^6 Btu × .356×10^6 Btu/HR × 5840 HR/YR	1240	
ELECTRICITY	$.015/KWH × 100 HP × .746 KW/HP × 5840 HR/YR	6540	
MAINTENANCE:			
GENERAL MAINT.	5% CAPITAL COST (291,000)	14,550	
MAINT. [illegible]	CATALYST	7800	
DIRECT LABOR:	.5 HR/SHIFT × 730 SHIFT/YR × $4/HR	1460	
SUPERVISION:	10% DIRECT LABOR	146	
DIRECT MFG. COST		31,736	
PAYROLL OVERHEAD	30% DIRECT LABOR	438	
PLANT OVERHEAD:	50% DIRECT LABOR	730	
PACKAGING:		–	
SHIPPING:		–	
INDIRECT MFG. COST		1168	
DEPRECIATION:	10% CAPITAL COST (295,400)	29,540	
PROPERTY TAXES:	1% CAPITAL COST (295,400)	2954	
INSURANCE:	0.5% CAPITAL COST (291,000)	1455	
FIXED MFG COST		33,949	
TOTAL PLANT LEVEL COST		66,853	
CORPORATE OVERHEAD	3% TOTAL PLANT LEVEL COST	2005	
TOTAL - MFG COST		68,858	
	LESS SAVINGS	25,900	
	FUEL SAVINGS 7.36×10^6 Btu/Hr × $.60/$10^6$ Btu × 5840 Hr/Yr = 25900	42,958	
	SAY	43,000	.0062

8-66

MANUFACTURING ESTIMATE - OVEN EXHAUST CONTROL SCHEME

CONTROL PROCESS: THERMAL INCINERATION w/o HEAT RECOV.- OVEN EXHAUST RATE: 1000 SCFM (15% LEL)

PROCESS OPERATING TIME: 2 SHIFTS/DAY 365 DAYS/YR 5840 HR/YR

ITEM	DESCRIPTION	COST $/YR	¢/M SCF
RAW MATERIALS			
UTILITIES:			
COOLING WATER	$.03/10³ GAL.		
STEAM	$1.00/10³ LB		
NATURAL GAS	$.60/10⁶ BTU × .882×10⁶ BTU/HR × 5840 HR/YR	3080	
ELECTRICITY	$.015/KWH × 5 HP × .746 KW/HP × 5840 HR/YR	327	
MAINTENANCE:			
GENERAL MAINT.	5% CAPITAL COST (20,000)	1000	
MAINT. SUPPLIES			
DIRECT LABOR:	.5 HR/SHIFT × 730 SHIFT/YR × $400/HR	1460	
SUPERVISION	10% DIRECT LABOR	146	
DIRECT MFG. COST		6013	
PAYROLL OVERHEAD	30% DIRECT LABOR	438	
PLANT OVERHEAD:	50% DIRECT LABOR	730	
PACKAGING:		–	
SHIPPING		–	
INDIRECT MFG. COST		1168	
DEPRECIATION:	10% CAPITAL COST (20,300)	2030	
PROPERTY TAXES:	1% CAPITAL COST (20,300)	203	
INSURANCE:	0.5% CAPITAL COST (20,000)	100	
FIXED MFG COST		2333	
TOTAL PLANT LEVEL COST		9514	
CORPORATE OVERHEAD	3% TOTAL PLANT LEVEL COST	285	
TOTAL - MFG COST		9799	
	SAY	9800	.028

MANUFACTURING ESTIMATE - OVEN EXHAUST CONTROL SCHEME

CONTROL PROCESS: THERMAL INCINERATION w/o HEAT RECOVERY - OVEN EXHAUST RATE: 10,000 SCFM (15% LEL)

PROCESS OPERATING TIME: 2 SHIFTS/DAY 365 DAYS/YR 5840 HR/YR

ITEM	DESCRIPTION	COST $/YR	COST $/M SCF
RAW MATERIALS			
UTILITIES:			
COOLING WATER	$.03/10³ GAL.		
STEAM	$1.00/10³ LB		
NATURAL GAS	$.60/10⁶ Btu × 8.8×10⁶ Btu/HR × 5840 HR/YR	30,800	
ELECTRICITY	$.015/KWH × 25 HP × .746 KW/HP × 5840 HR/YR	1,635	
MAINTENANCE:			
GENERAL MAINT.	5% CAPITAL COST (40,000)	2,000	
MAINT. SUPPLIES			
DIRECT LABOR:	.5 HR/SHIFT × 730 SHIFT/YR × $4.00/HR	1,460	
SUPERVISION:	10% DIRECT LABOR	146	
DIRECT MFG. COST		36041	
PAYROLL OVERHEAD	30% DIRECT LABOR	438	
PLANT OVERHEAD:	50% DIRECT LABOR	730	
PACKAGING:		-	
SHIPPING:		-	
INDIRECT MFG. COST		1168	
DEPRECIATION:	10% CAPITAL COST (40,600)	4060	
PROPERTY TAXES:	1% CAPITAL COST (40,600)	406	
INSURANCE:	0.5% CAPITAL COST (40,000)	200	
FIXED MFG COST		4666	
TOTAL PLANT LEVEL COST		41875	
CORPORATE OVERHEAD	3% TOTAL PLANT LEVEL COST	1256	
TOTAL-MFG COST		43,131	
	SAY	43,100	.0123

MANUFACTURING ESTIMATE - OVEN EXHAUST CONTROL SCHEME

CONTROL PROCESS: THERMAL INCINERATION w/o HEAT RECOVERY - OVEN EXHAUST RATE - 20,000 SCFM (15%LEL)

PROCESS OPERATING TIME: 2 SHIFTS/DAY 365 DAYS/YR 5840 HR/YR

ITEM	DESCRIPTION	COST $/YR	COST $/M SCF
RAW MATERIALS			
UTILITIES:			
COOLING WATER	$.03/10³ GAL.		
STEAM	$1.00/10³ LB		
NATURAL GAS	$.60/10⁶ Btu × 16.44 × 10⁶ Btu/Hr × 5840 Hr/Yr	61,600	
ELECTRICITY	$.015/KWH × 50 HP × .746 KW/HP × 5840 Hr/Yr	3,270	
MAINTENANCE:			
GENERAL MAINT.	5% CAPITAL COST (50,000)	2,500	
MAINT. SUPPLIES			
DIRECT LABOR:	.5 Hr/SHIFT × 730 SHIFT/YR × $4.00/Hr	1460	
SUPERVISION:	10% DIRECT LABOR	146	
DIRECT MFG. COST		68976	
PAYROLL OVERHEAD	30% DIRECT LABOR	438	
PLANT OVERHEAD:	50% DIRECT LABOR	730	
PACKAGING:		-	
SHIPPING:		-	
INDIRECT MFG. COST		1168	
DEPRECIATION:	10% CAPITAL COST (50,750)	5075	
PROPERTY TAXES:	1% CAPITAL COST (50,750)	508	
INSURANCE:	0.5% CAPITAL COST (50,000)	250	
FIXED MFG COST		5833	
TOTAL PLANT LEVEL COST		75977	
CORPORATE OVERHEAD	3% TOTAL PLANT LEVEL COST	2279	
TOTAL-MFG COST		78,256	
	SAY	78,300	.0112

MANUFACTURING ESTIMATE - OVEN EXHAUST CONTROL SCHEME

CONTROL PROCESS: THERMAL INCINERATION - PRIMARY HEAT RECOVERY ; OVEN EXHAUST RATE 1000 SCFM (15% LEL)

PROCESS OPERATING TIME: 2 SHIFTS/DAY 365 DAYS/YR 5840 HR/YR

ITEM	DESCRIPTION	COST	
		$/YR	$/M SCF
RAW MATERIALS			
UTILITIES:			
COOLING WATER	$.03/10³ GAL.		
STEAM	$1.00/10³ LB		
NATURAL GAS	$.60/10⁶ Btu × .273×10⁶ Btu/HR × 5840 HR/YR	960	
ELECTRICITY	$.015/KWH × 5HP × .746 KW/HP × 5840 HR/YR	327	
MAINTENANCE:			
GENERAL MAINT.	5% CAPITAL COST (37,000)	1850	
MAINT. SUPPLIES			
DIRECT LABOR:	.5 HR/SHIFT × 730 SHIFT/YR × $4.00/HR	1460	
SUPERVISION:	10% DIRECT LABOR	146	
DIRECT MFG. COST		4743	
PAYROLL OVERHEAD	30% DIRECT LABOR	438	
PLANT OVERHEAD:	50% DIRECT LABOR	730	
PACKAGING:		-	
SHIPPING:		-	
INDIRECT MFG. COST		1168	
DEPRECIATION:	10% CAPITAL COST (37,560)	3756	
PROPERTY TAXES:	1% CAPITAL COST (37,560)	376	
INSURANCE:	0.5% CAPITAL COST (37,000	185	
FIXED MFG COST		4,317	
TOTAL PLANT LEVEL COST		10,228	
CORPORATE OVERHEAD	3% TOTAL PLANT LEVEL COST	307	
TOTAL-MFG COST		10,535	
	SAY	10,500	.03

MANUFACTURING ESTIMATE - OVEN EXHAUST CONTROL SCHEME

CONTROL PROCESS: THERMAL INCINERATION - PRIMARY HEAT RECOVERY - OVEN EXHAUST RATE - 10,000 SCFM (15% LEL)

PROCESS OPERATING TIME: 2 SHIFTS/DAY 365 DAYS/YR 5840 HR/YR

ITEM	DESCRIPTION	COST	
		$/YR	$/M SCF
RAW MATERIALS			
UTILITIES:			
COOLING WATER	$.03/10³ GAL.		
STEAM	$1.00/10³ LB		
NATURAL GAS	$.60/10⁶ BTU x 2.73x10⁶ BTU/HR x 5840 HR/YR	9600	
ELECTRICITY	$.015/KWH x 25 HP x .746 KW/HP x 5840 HR/YR	1635	
MAINTENANCE:		5000	
GENERAL MAINT.	5% CAPITAL COST (100,000)		
MAINT. SUPPLIES			
DIRECT LABOR:	.5 HR/SHIFT x 730 SHIFT/YR $4/HR	1460	
SUPERVISION:	10% DIRECT LABOR	146	
DIRECT MFG. COST		17841	
PAYROLL OVERHEAD	30% DIRECT LABOR	438	
PLANT OVERHEAD:	50% DIRECT LABOR	730	
PACKAGING:		-	
SHIPPING:		-	
INDIRECT MFG. COST		1168	
DEPRECIATION:	10% CAPITAL COST (101,500)	10150	
PROPERTY TAXES:	1% CAPITAL COST (101,500)	1015	
INSURANCE:	0.5% CAPITAL COST (100,000)	500	
FIXED MFG COST		11665	
TOTAL PLANT LEVEL COST		30674	
CORPORATE OVERHEAD	3% TOTAL PLANT LEVEL COST	920	
TOTAL MFG COST		31594	
	SAY	31,600	.009

MANUFACTURING ESTIMATE - OVEN EXHAUST CONTROL SCHEME

CONTROL PROCESS: THERMAL INCINERATION - PRIMARY HEAT RECOVERY - OVEN EXHAUST RATE 20,000 SCFM (15% LEL)

PROCESS OPERATING TIME: 2 SHIFTS/DAY 365 DAYS/YR 5840 HR/YR

ITEM	DESCRIPTION	COST $/YR	COST $/M SCF
RAW MATERIALS			
UTILITIES:			
COOLING WATER	$.03/10² GAL.		
STEAM	$1.00/10³ LB		
NATURAL GAS	$.60/10⁶ Btu × 5.46 × 10⁶ Btu/Hr × 5840 HR/YR	19,200	
ELECTRICITY	$.015/KWH × 50HP × .746 KW/HP × 5840 HR/YR	3270	
MAINTENANCE:			
GENERAL MAINT.	5% CAPITAL COST (140,000)	7000	
MAINT. SUPPLIES			
DIRECT LABOR:	.5 HR/SHIFT × 730 SHIFT/YR × $4/HR	1460	
SUPERVISION:	10% DIRECT LABOR	146	
DIRECT MFG. COST		31,076	
PAYROLL OVERHEAD:	30% DIRECT LABOR	438	
PLANT OVERHEAD:	50% DIRECT LABOR	730	
PACKAGING:		-	
SHIPPING:		-	
INDIRECT MFG. COST		1168	
DEPRECIATION:	10% CAPITAL COST (142,100)	14210	
PROPERTY TAXES:	1% CAPITAL COST (142,100)	1421	
INSURANCE:	0.5% CAPITAL COST (140,000)	700	
FIXED MFG COST		16,331	
TOTAL PLANT LEVEL COST		48,575	
CORPORATE OVERHEAD	3% TOTAL PLANT LEVEL COST	1457	
TOTAL MFG COST		50,032	
	SAY	50,000	.007

MANUFACTURING ESTIMATE - OVEN EXHAUST CONTROL SCHEME

CONTROL PROCESS: THERMAL INCINERATION - PRIMARY & SECONDARY HEAT RECOVERY - OVEN EXHAUST RATE = 1000 SCFM (15% LEL)

PROCESS OPERATING TIME: 2 SHIFTS/DAY 365 DAYS/YR 5840 HR/YR

ITEM	DESCRIPTION	COST $/YR	 $/M SCF
RAW MATERIALS			
UTILITIES:			
COOLING WATER	$.03/$10^3$ GAL.		
STEAM	$1.00/$10^3$ LB		
NATURAL GAS	$.60/$10^6$ Btu × .273×10^6 Btu/HR × 5840 HR/YR	960	
ELECTRICITY	$.015/KWH × 10 HP × .746 KW/HP × 5840 HR/YR	654	
MAINTENANCE:			
GENERAL MAINT.	5% CAPITAL COST (52,800)	2640	
MAINT. SUPPLIES			
DIRECT LABOR:	.5 HR/SHIFT × 730 SHIFT/YR × $4/HR	1460	
SUPERVISION:	10% DIRECT LABOR	146	
DIRECT MFG. COST		5860	
PAYROLL OVERHEAD:	30% DIRECT LABOR	438	
PLANT OVERHEAD:	50% DIRECT LABOR	730	
PACKAGING:		-	
SHIPPING:		-	
INDIRECT MFG. COST		1168	
DEPRECIATION:	10% CAPITAL COST (53,590)	5359	
PROPERTY TAXES:	1% CAPITAL COST (53,590)	536	
INSURANCE:	0.5% CAPITAL COST (52,800)	264	
FIXED MFG COST		6159	
TOTAL PLANT LEVEL COST		13,187	
CORPORATE OVERHEAD	3% TOTAL PLANT LEVEL COST	396	
TOTAL - MFG COST		13,583	
	FUEL SAVINGS: $.60/$10^6$ Btu × .368×10^6 Btu/HR × 5840 HR/YR = 1295 LESS SAVINGS	1295	
		12288	
	SAY	12,300	.035

MANUFACTURING ESTIMATE - OVEN EXHAUST CONTROL SCHEME

CONTROL PROCESS: THERMAL INCINERATION - PRIMARY & SECONDARY HEAT RECOVERY - OVEN EXHAUST

PROCESS OPERATING TIME: 2 SHIFTS/DAY 365 DAYS/YR 5840 HR/YR

RATE: 10,000 SCFM (15% LEL)

ITEM	DESCRIPTION	COST	
		$/YR	$/M SC
RAW MATERIALS			
UTILITIES:			
COOLING WATER	$\$.03/10^{3}$ GAL.		
STEAM	$\$1.00/10^{3}$ LB		
NATURAL GAS	$\$.60/10^{6}$ Btu × 2.73×10^{6} Btu/HR × 5840 HR/YR	9600	
ELECTRICITY	$.015/KWH × 50 HP × .746 KW/HP × 5840 HR/YR	3270	
MAINTENANCE:			
GENERAL MAINT.	5% CAPITAL COST (156,000)	7800	
MAINT. SUPPLIES			
DIRECT LABOR:	.5 HR/SHIFT × 730 SHIFT/YR × $4.00/HR	1460	
SUPERVISION:	10% DIRECT LABOR	146	
DIRECT MFG. COST		22,276	
PAYROLL OVERHEAD	30% DIRECT LABOR	438	
PLANT OVERHEAD:	50% DIRECT LABOR	730	
PACKAGING:		-	
SHIPPING:		-	
INDIRECT MFG. COST		1168	
DEPRECIATION:	10% CAPITAL COST (158,340)	15,834	
PROPERTY TAXES:	1% CAPITAL COST (158,340)	1,583	
INSURANCE:	0.5% CAPITAL COST (156,000)	780	
FIXED MFG COST		18197	
TOTAL PLANT LEVEL COST		41,641	
CORPORATE OVERHEAD	3% TOTAL PLANT LEVEL COST	1249	
TOTAL-MFG COST		42890	
	FUEL SAVINGS LESS SAVINGS	12,950	
		29,940	
	$\$.60/10^{6}$ Btu × 3.68×10^{6} Btu/HR × 5840 HR/YR = 12,950		
	SAY	29,900	.0185

MANUFACTURING ESTIMATE - OVEN EXHAUST CONTROL SCHEME

CONTROL PROCESS: THERMAL INCINERATION - PRIMARY & SECONDARY HEAT RECOVERY - OVEN EXHAUST

RATE - 29000 SCFM (15% LEL)

PROCESS OPERATING TIME: 2 SHIFTS/DAY 365 DAYS/YR 5840 HR/YR

		COST	
ITEM	DESCRIPTION	$/YR	$/MSCF
RAW MATERIALS			
UTILITIES:			
COOLING WATER	$\$.03/10^3$ GAL.		
STEAM	$\$1.00/10^3$ LB		
NATURAL GAS	$\$.60/10^6$ Btu × 5.46 × 10^6 Btu/HR × 5840 HR/YR	19,200	
ELECTRICITY	$.015/KWH × 100 HP × .746 KW/HP × 5840 HR/YR	6540	
MAINTENANCE:			
GENERAL MAINT.	5% CAPITAL COST (225,000)	11,250	
MAINT. SUPPLIES			
DIRECT LABOR:	.5 HR/SHIFT × 730 SHIFT/YR × $4.00	1460	
SUPERVISION:	10% DIRECT LABOR	146	
DIRECT MFG. COST		38596	
PAYROLL OVERHEAD:	30% DIRECT LABOR	438	
PLANT OVERHEAD:	50% DIRECT LABOR	730	
PACKAGING:		-	
SHIPPING:		-	
INDIRECT MFG. COST		1168	
DEPRECIATION:	10% CAPITAL COST (228,400)	22840	
PROPERTY TAXES:	1% CAPITAL COST (228,400)	2284	
INSURANCE:	0.5% CAPITAL COST (225,000)	1125	
FIXED MFG COST		26,249	
TOTAL PLANT LEVEL COST		66,013	
CORPORATE OVERHEAD	3% TOTAL PLANT LEVEL COST	1,980	
TOTAL MFG COST		67,993	
	LESS SAVINGS	25,900	
	FUEL SAVINGS $\$.60/10^6$ Btu × 7.36 × 10^6 Btu/HR × 5840 HR/YR = 25,900	42093	
	SAY	42,100	.006

MANUFACTURING ESTIMATE - OVEN EXHAUST CONTROL SCHEME

CONTROL PROCESS: CATALYTIC INCINERATION WITHOUT HEAT RECOVERY ~ OVEN EXHAUST RATE: 1000 SCFM (25% LEL)

PROCESS OPERATING TIME: 2 SHIFTS/DAY 365 DAYS/YR 5840 HR/YR

ITEM	DESCRIPTION	COST	
		$/YR	$/M SCF
RAW MATERIALS			
UTILITIES:			
COOLING WATER	$.03/10³ GAL.		
STEAM	$1.00/10³ LB		
NATURAL GAS	$.60/10⁶ Btu × .332×10⁶ Btu/HR × 5840 HR/YR = $1165	1165	
ELECTRICITY	$.015/KWH × 3HP × .746 KW/HP × 5840 HR/YR = $196	196	
MAINTENANCE:			
GENERAL MAINT.	5% CAPITAL COST (32,000)	1600	
MAINT. SUPPLIES	CATALYST $2000/YR	2000	
DIRECT LABOR:	.5 HR/SHIFT × 730 SHIFT/YR × $4.00/HR	1460	
SUPERVISION:	10% DIRECT LABOR	146	
DIRECT MFG. COST		6567	
PAYROLL OVERHEAD	30% DIRECT LABOR	438	
PLANT OVERHEAD:	50% DIRECT LABOR	730	
PACKAGING:		–	
SHIPPING:		–	
INDIRECT MFG. COST		1168	
DEPRECIATION:	10% CAPITAL COST (32,480)	3248	
PROPERTY TAXES:	1% CAPITAL COST (32,480)	325	
INSURANCE:	0.5% CAPITAL COST (32,000)	160	
FIXED MFG COST		3733	
TOTAL PLANT LEVEL COST		11,468	
CORPORATE OVERHEAD	3% TOTAL PLANT LEVEL COST	344	
TOTAL MFG COST		11,812	
	SAY	11,800	.0337

MANUFACTURING ESTIMATE - OVEN EXHAUST CONTROL SCHEME

CONTROL PROCESS: CATALYTIC INCINERATION WITHOUT HEAT RECOVERY ~ OVEN EXHAUST RATE ~ 10,000 SCFM (25% LEL)

PROCESS OPERATING TIME: 2 SHIFTS/DAY 365 DAYS/YR 5840 HR/YR

ITEM	DESCRIPTION	COST $/YR	COST $/M SCF
RAW MATERIALS			
UTILITIES:			
COOLING WATER	$.03/$10^3$ GAL.		
STEAM	$1.00/$10^3$ LB		
NATURAL GAS	$.60/$10^6$ Btu × 3.32 × 106 Btu/Hr × 5840 Hr/Yr = 11,650	11,650	
ELECTRICITY	$.015/KWH × 25 HP × .746 KW/HP × 5840 Hr/Yr	1,630	
MAINTENANCE:			
GENERAL MAINT.	5% CAPITAL COST (200,000)	10,000	
MAINT. SUPPLIES	CATALYST $23,333/YR	23,333	
DIRECT LABOR:	.5 HR/SHIFT × 730 SHIFT/YR × $4.00/HR	1460	
SUPERVISION:	10% DIRECT LABOR	146	
DIRECT MFG. COST		48,219	
PAYROLL OVERHEAD	30% DIRECT LABOR	438	
PLANT OVERHEAD:	50% DIRECT LABOR	730	
PACKAGING:		–	
SHIPPING:		–	
INDIRECT MFG. COST		1168	
DEPRECIATION:	10% CAPITAL COST (203,000)	20300	
PROPERTY TAXES:	1% CAPITAL COST (203,000)	2030	
INSURANCE:	0.5% CAPITAL COST (200,000)	1000	
FIXED MFG COST		23330	
TOTAL PLANT LEVEL COST		72,717	
CORPORATE OVERHEAD	3% TOTAL PLANT LEVEL COST	2181	
TOTAL-MFG COST		74,898	
	SAY	74,900	.0211

MANUFACTURING ESTIMATE - OVEN EXHAUST CONTROL SCHEME

CONTROL PROCESS: CATALYTIC INCINERATION WITHOUT HEAT RECOVERY ~ OVEN EXHAUST RATE ~20,000 SCFM

PROCESS OPERATING TIME: 2 SHIFTS/DAY 365 DAYS/YR 5840 HR/YR

(25% LEL)

ITEM	DESCRIPTION	COST $/YR	 $/MSCF
RAW MATERIALS			
UTILITIES:			
COOLING WATER	$.03/$10^3$ GAL.		
STEAM	$1.00/$10^3$ LB		
NATURAL GAS	$ .60/10^6 Btu × 6.64×10^6 Btu/Hr × 5840 Hr/yr	23,300	
ELECTRICITY	$.015/KWH × 50HP × .746 KW/HP × 5840 Hr/yr	3,260	
MAINTENANCE:			
GENERAL MAINT.	5% CAPITAL COST (371,000)	18,550	
MAINT. SUPPLIES	CATALYST	46,667	
DIRECT LABOR:	.5 HR/SHIFT × 730 SHIFT/YR × $4.00/HR	1,460	
SUPERVISION:	10% DIRECT LABOR	146	
DIRECT MFG. COST		93383	
PAYROLL OVERHEAD	30% DIRECT LABOR	438	
PLANT OVERHEAD:	50% DIRECT LABOR	730	
PACKAGING:		–	
SHIPPING:		–	
INDIRECT MFG. COST		1168	
DEPRECIATION:	10% CAPITAL COST (376,600)	37,660	
PROPERTY TAXES:	1% CAPITAL COST (376,600)	3766	
INSURANCE:	0.5% CAPITAL COST (371,000)	1855	
FIXED MFG COST		43281	
TOTAL PLANT LEVEL COST		137832	
CORPORATE OVERHEAD	3% TOTAL PLANT LEVEL COST	4135	
TOTAL-MFG COST		141,967	
	Say	142,000	.0203

MANUFACTURING ESTIMATE - OVEN EXHAUST CONTROL SCHEME

CONTROL PROCESS: CATALYTIC INCINERATION WITH PRIMARY HEAT RECOVERY ~ OVEN EXHAUST RATE 1000 SCFM (25% LEL)

PROCESS OPERATING TIME: 2 SHIFTS/DAY 365 DAYS/YR. 5940 HR/YR

ITEM	DESCRIPTION	COST $/YR	$/M SC
RAW MATERIALS			
UTILITIES:			
COOLING WATER	$.03/10³ GAL.		
STEAM	$1.00/10³ LB		
NATURAL GAS	$.60/10⁶ BTU		
ELECTRICITY	$.015/KWH × 5 HP × .746 KW/HP × 5840 HR/YR	326	
MAINTENANCE:			
GENERAL MAINT.	5% CAPITAL COST (39,800)	1990	
MAINT. SUPPLIES	CATALYST	2000	
DIRECT LABOR:	.5 HR/SHIFT × 730 SHIFTS/YR × $4.00/HR	1460	
SUPERVISION:	10% DIRECT LABOR	146	
DIRECT MFG. COST		5922	
PAYROLL OVERHEAD	30% DIRECT LABOR	438	
PLANT OVERHEAD:	50% DIRECT LABOR	730	
PACKAGING:		–	
SHIPPING:		–	
INDIRECT MFG. COST		1168	
DEPRECIATION:	10% CAPITAL COST (40,400)	4040	
PROPERTY TAXES:	1% CAPITAL COST (40,400)	404	
INSURANCE:	0.5% CAPITAL COST (39,800)	199	
FIXED MFG COST		4643	
TOTAL PLANT LEVEL COST		11,733	
CORPORATE OVERHEAD	3% TOTAL PLANT LEVEL COST	352	
TOTAL MFG COST		12085	
	SA-1	12,100	.0344

MANUFACTURING ESTIMATE - OVEN EXHAUST CONTROL SCHEME

CONTROL PROCESS: CATALYTIC INCINERATION WITH PRIMARY HEAT RECOVERY - OVEN EXHAUST RATE 10,000 SCFM (25% LEL)

PROCESS OPERATING TIME: 2 SHIFTS/DAY 365 DAYS/YR 5840 HR/YR

ITEM	DESCRIPTION	COST	
		$/YR	$/MSCF
RAW MATERIALS			
UTILITIES:			
COOLING WATER	$.03/$10^3$ GAL.		
STEAM	$1.00/$10^3$ LB		
NATURAL GAS	$.60/$10^6$ Btu		
ELECTRICITY	$.015/KWH × 50 HP × .746 KW/HP × 5840 HR/YR	3,260	
MAINTENANCE:			
GENERAL MAINT.	5% CAPITAL COST (225,000)	11,250	
MAINT. SUPPLIES	CATALYST	23,333	
DIRECT LABOR:	.5 HR/SHIFT × 730 SHIFT/YEAR × $4.00/HR	1,460	
SUPERVISION:	10% DIRECT LABOR	146	
DIRECT MFG. COST		39,449	
PAYROLL OVERHEAD:	30% DIRECT LABOR	438	
PLANT OVERHEAD:	50% DIRECT LABOR	730	
PACKAGING:		–	
SHIPPING:		–	
INDIRECT MFG. COST		1168	
DEPRECIATION:	10% CAPITAL COST (228,400)	22,840	
PROPERTY TAXES:	1% CAPITAL COST (228,400)	2,284	
INSURANCE:	0.5% CAPITAL COST (225,000)	1,125	
FIXED MFG COST		26,249	
TOTAL PLANT LEVEL COST		66,866	
CORPORATE OVERHEAD	3% TOTAL PLANT LEVEL COST	2,006	
TOTAL-MFG COST		68,872	
	SAY	68,900	.0197

MANUFACTURING ESTIMATE - OVEN EXHAUST CONTROL SCHEME

CONTROL PROCESS: CATALYTIC INCINERATION WITH PRIMARY HEAT RECOVERY~ OVEN EXHAUST RATE~20,000 SCFM (25% LEL)

PROCESS OPERATING TIME: 2 SHIFTS/DAY 365 DAYS/YR 5840 HR/YR

ITEM	DESCRIPTION	COST	
		$/YR	$/MSCF
RAW MATERIALS			
UTILITIES:			
COOLING WATER	$.03/10³ GAL.		
STEAM	$1.00/10³ LB		
NATURAL GAS	$.60/10⁶ BTU		
ELECTRICITY	$.015/KWH × 100 HP × .746 KW/HP × 5840 HR/YR	6,520	
MAINTENANCE:			
GENERAL MAINT.	5% CAPITAL COST (422,000)	21,100	
MAINT. SUPPLIES	CATALYST	46,666	
DIRECT LABOR:	.5 HR/SHIFT × 730 SHIFT/YR × $4.00/HR	1,460	
SUPERVISION:	10% DIRECT LABOR	146	
DIRECT MFG. COST		75,892	
PAYROLL OVERHEAD	30% DIRECT LABOR	438	
PLANT OVERHEAD:	50% DIRECT LABOR	730	
PACKAGING:		-	
SHIPPING:		-	
INDIRECT MFG. COST		1138	
DEPRECIATION:	10% CAPITAL COST (428,330)	42,833	
PROPERTY TAXES:	1% CAPITAL COST (428,330)	4,283	
INSURANCE:	0.5% CAPITAL COST (422,000)	2,110	
FIXED MFG COST		49226	
TOTAL PLANT LEVEL COST		126,256	
CORPORATE OVERHEAD	3% TOTAL PLANT LEVEL COST	3788	
TOTAL-MFG COST		130,044	
	SAY	130,000	.0186

MANUFACTURING ESTIMATE - OVEN EXHAUST CONTROL SCHEME

CONTROL PROCESS: CATALYTIC INCINERATION WITH PRIMARY & SECONDARY HEAT RECOVERY ON OVEN EXHAUST RATE - 1000 SCFM (25% LEL)

PROCESS OPERATING TIME: 3 SHIFTS/DAY 730 DAYS/YR 5940 HR/YR

ITEM	DESCRIPTION	COST $/YR	COST $/M SCF
RAW MATERIALS			
UTILITIES:			
COOLING WATER	$.03/10³ GAL.		
STEAM	$1.00/10³ LB		
NATURAL GAS	$.60/10⁶ Btu		
ELECTRICITY	$.015/KWH × 10 HP × .746 KW/HP × 5840 HR/YR	652	
MAINTENANCE:		2510	
GENERAL MAINT.	5% CAPITAL COST (50,200)		
MAINT. SUPPLIES	CATALYST	2000	
DIRECT LABOR:	.5 HR/SHIFT × 730 SHIFT/YR × $4.00/HR	1460	
SUPERVISION:	10% DIRECT LABOR	146	
DIRECT MFG. COST		6768	
PAYROLL OVERHEAD	30% DIRECT LABOR	438	
PLANT OVERHEAD:	50% DIRECT LABOR	730	
PACKAGING:			
SHIPPING:			
INDIRECT MFG. COST		1168	
DEPRECIATION:	10% CAPITAL COST (50,950)	5095	
PROPERTY TAXES:	1% CAPITAL COST (50,950)	510	
INSURANCE:	0.5% CAPITAL COST (50,200)	251	
FIXED MFG COST		5856	
TOTAL PLANT LEVEL COST		13,792	
CORPORATE OVERHEAD	3% TOTAL PLANT LEVEL COST	414	
TOTAL-MFG COST		14,206	
	FUEL SAVINGS: $.367 \times 10^6 \frac{Btu}{HR} \times \$.60/10^6\ Btu \times 5840 \frac{HR}{YR} = \$1290/YR$ LESS SAVINGS	1,290	
		12,916	
	SAY	$12,900	.0369

MANUFACTURING ESTIMATE - OVEN EXHAUST CONTROL SCHEME

CONTROL PROCESS: CATALYTIC INCINERATION WITH PRIMARY & SECONDARY HEAT RECOVERY ~ OVEN EXHAUST RATE ~ 10,000 SCFM (25% LEL)

PROCESS OPERATING TIME: 2 SHIFTS/DAY 365 DAYS/YR 5840 HR/YR

ITEM	DESCRIPTION		COST $/YR	COST $/M SCF
RAW MATERIALS				
UTILITIES:				
COOLING WATER	$.03/$10^3$ GAL.			
STEAM	$1.00/$10^3$ LB			
NATURAL GAS	$.60/$10^6$ Btu			
ELECTRICITY	$.015/KWH × 100 HP × .746 KW/HP × 5840 HR/YR =		6520	
MAINTENANCE:				
GENERAL MAINT.	5% CAPITAL COST (266,000)		13,300	
MAINT. SUPPLIES	CATALYST		23,333	
DIRECT LABOR:	.5 HR/SHIFT × 730 SHIFT/YR × $4.00/HR		1460	
SUPERVISION:	10% DIRECT LABOR		146	
DIRECT MFG. COST			44,759	
PAYROLL OVERHEAD	30% DIRECT LABOR		438	
PLANT OVERHEAD:	50% DIRECT LABOR		730	
PACKAGING:			–	
SHIPPING:			–	
INDIRECT MFG. COST			1,168	
DEPRECIATION:	10% CAPITAL COST (269,990)		26,999	
PROPERTY TAXES:	1% CAPITAL COST (269,990)		2700	
INSURANCE:	0.5% CAPITAL COST (266,000)		1330	
FIXED MFG COST			31,029	
TOTAL PLANT LEVEL COST			76,956	
CORPORATE OVERHEAD	3% TOTAL PLANT LEVEL COST		2,309	
TOTAL - MFG COST			[illegible]9,265	
	FUEL SAVINGS: 3.67 × 10^6 Btu/HR × $.60/$10^6$ Btu × 5840 HR/YR = $12,900	LESS SAVINGS	12,900	
			66,365	
		SAY	66,400	.019

MANUFACTURING ESTIMATE - OVEN EXHAUST CONTROL SCHEME

CONTROL PROCESS: CATALYTIC INCINERATION WITH PRIMARY & SECONDARY HEAT RECOVERY ~ OVEN EXHAUST RATE ~ 20,000 SCFM (25% LEL

PROCESS OPERATING TIME: 2 SHIFTS/DAY 365 DAYS/YR 5840 HR/YR

ITEM	DESCRIPTION	COST	
		$/YR.	$/M S
RAW MATERIALS			
UTILITIES:			
COOLING WATER	$.03/$10^3$ GAL.		
STEAM	$1.00/$10^3$ LB		
NATURAL GAS	$.60/$10^6$ Btu		
ELECTRICITY	$.015/KWH × 200 HP × .746 KW/HP × 5840 HR/YR	13,040	
MAINTENANCE:			
GENERAL MAINT.	5% CAPITAL COST (490,000)	24,500	
MAINT. SUPPLIES	CATALYST	46,666	
DIRECT LABOR:	.5 HR/SHIFT × 730 SHIFT/YR × $4.00/HR	1,460	
SUPERVISION:	10% DIRECT LABOR	146	
DIRECT MFG. COST		85812	
PAYROLL OVERHEAD	30% DIRECT LABOR	438	
PLANT OVERHEAD:	50% DIRECT LABOR	730	
PACKAGING:		–	
SHIPPING:		–	
INDIRECT MFG. COST		1168	
DEPRECIATION:	10% CAPITAL COST (497,350)	49735	
PROPERTY TAXES:	1% CAPITAL COST (497,350)	4974	
INSURANCE:	0.5% CAPITAL COST (490,000)	2450	
FIXED MFG COST		57,159	
TOTAL PLANT LEVEL COST		144,139	
CORPORATE OVERHEAD	3% TOTAL PLANT LEVEL COST	4,324	
TOTAL-MFG COST		148,463	
	LESS SAVINGS	25,800	
	FUEL SAVINGS 7.34×10^6 Btu/Hr × $.60/$10^6$ Btu × 5840 Hr/Yr $25,800	122,663	
	SAY	122,700	.0175

MANUFACTURING ESTIMATE - OVEN EXHAUST CONTROL SCHEME

CONTROL PROCESS: THERMAL INCINERATION WITHOUT HEAT RECOVERY ~ OVEN EXHAUST RATE 1000 SCFM

PROCESS OPERATING TIME: 2 SHIFTS/DAY 365 DAYS/YR 5840 HR/YR

(25% LEL)

ITEM	DESCRIPTION	COST	
		$/YR	$/M SCF
RAW MATERIALS		-	
UTILITIES:			
COOLING WATER	$.03/10³ GAL.	-	
STEAM	$1.00/10³ LB	-	
NATURAL GAS	$.60/10⁶ Btu × 5840 HR/YR × .629 × 10⁶ BTU/HR	2210	
ELECTRICITY	$.015/KWH × 3 HP × .746 KW/HP × 5840 HR/YR	195	
MAINTENANCE:			
GENERAL MAINT.	5% CAPITAL COST (20,000)	1000	
MAINT. SUPPLIES	-	—	
DIRECT LABOR:	.5 HR/SHIFT × 720 SHIFT/YR × $4.00/HR	1460	
SUPERVISION:	10% DIRECT LABOR	146	
DIRECT MFG. COST		5011	
PAYROLL OVERHEAD:	30% DIRECT LABOR	438	
PLANT OVERHEAD:	50% DIRECT LABOR	730	
PACKAGING:		-	
SHIPPING:		-	
INDIRECT MFG. COST		1168	
DEPRECIATION:	10% CAPITAL COST (20,300)	2030	
PROPERTY TAXES:	1% CAPITAL COST (20,300)	203	
INSURANCE:	0.5% CAPITAL COST (20,000)	100	
FIXED MFG COST		2333	
TOTAL PLANT LEVEL COST		8,512	
CORPORATE OVERHEAD	3% TOTAL PLANT LEVEL COST	255	
TOTAL-MFG COST		8,767	
	SAY	8800	.0292

MANUFACTURING ESTIMATE - OVEN EXHAUST CONTROL SCHEME

CONTROL PROCESS: THERMAL INCINERATION WITHOUT HEAT RECOVERY ~ OVEN EXHAUST RATE: 10,000 SCFM

PROCESS OPERATING TIME: 2 SHIFTS/DAY 365 DAYS/YR 5840 HR/YR

(25% LEL)

ITEM	DESCRIPTION	COST	
		$/YR	$/M SCF
RAW MATERIALS			
UTILITIES:			
COOLING WATER	$.03/$10^3$ GAL.	–	
STEAM	$ 1.00/10^3 LB	–	
NATURAL GAS	$ .60/10^6 Btu × 6.29×10^6 Btu/HR × 5840 HR/YR =	22,100	
ELECTRICITY	$.015/KWH × 25 HP × .746 KW/HP × 5840 HR/YR =	1,640	
MAINTENANCE:			
GENERAL MAINT.	5% CAPITAL COST (68,000)	3,400	
MAINT. SUPPLIES	–	–	
DIRECT LABOR:	.5 HR/SHIFT × 730 SHIFT/YR × $4.00/HR	1460	
SUPERVISION:	10% DIRECT LABOR	146	
DIRECT MFG. COST		28,746	
PAYROLL OVERHEAD	30% DIRECT LABOR	438	
PLANT OVERHEAD:	50% DIRECT LABOR	730	
PACKAGING:		–	
SHIPPING:		–	
INDIRECT MFG. COST		1168	
DEPRECIATION:	10% CAPITAL COST (69,000)	6900	
PROPERTY TAXES:	1% CAPITAL COST (69,000)	690	
INSURANCE:	0.5% CAPITAL COST (68,000)	340	
FIXED MFG COST		7930	
TOTAL PLANT LEVEL COST		37,844	
CORPORATE OVERHEAD	3% TOTAL PLANT LEVEL COST	1135	
TOTAL-MFG COST		38979	
	SAY	39,000	.011

MANUFACTURING ESTIMATE - OVEN EXHAUST CONTROL SCHEME

CONTROL PROCESS: THERMAL INCINERATION WITHOUT HEAT RECOVERY ~ OVEN EXHAUST RATE 20,000 SCFM

PROCESS OPERATING TIME: 2 SHIFTS/DAY 365 DAYS/YR 5840 HR/YR (25 LEL)

ITEM	DESCRIPTION	COST $/YR	COST $/MSCF
RAW MATERIALS			
UTILITIES:		—	
COOLING WATER	$.03/$10^3$ GAL.	—	
STEAM	$ 1.00/10^3 LB		
NATURAL GAS	$ .60/10^6 Btu × 12.58 × 10^6 Btu/HR × 5840 HR/YR	44,000	
ELECTRICITY	$ .015/KWHR 50 HP × .746 KW/HP × 5840 HR/YR	3260	
MAINTENANCE:			
GENERAL MAINT.	5% CAPITAL COST (101,000)	5050	
MAINT. SUPPLIES		—	
DIRECT LABOR:	.5 HR/SHIFT × 730 SHIFTS/YR × $4.00/HR	1460	
SUPERVISION:	10% DIRECT LABOR	146	
DIRECT MFG. COST		53916	
PAYROLL OVERHEAD:	30% DIRECT LABOR	438	
PLANT OVERHEAD:	50% DIRECT LABOR	730	
PACKAGING:		—	
SHIPPING:		—	
INDIRECT MFG. COST		1168	
DEPRECIATION:	10% CAPITAL COST (102,500)	10,250	
PROPERTY TAXES:	1% CAPITAL COST (102,500)	1,025	
INSURANCE:	0.5% CAPITAL COST (101,000)	505	
FIXED MFG COST		11,880	
TOTAL PLANT LEVEL COST		66,964	
CORPORATE OVERHEAD	3% TOTAL PLANT LEVEL COST	2,009	
TOTAL-MFG COST		68,973	
	SAY	69,000	.0099

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MANUFACTURING ESTIMATE - OVEN EXHAUST CONTROL SCHEME

CONTROL PROCESS: THERMAL INCINERATION WITH PRIMARY HEAT RECOVERY ON OVEN EXHAUST RATES 1000 SCFM

PROCESS OPERATING TIME: 2 SHIFTS/DAY 365 DAYS/YR 5840 HR/YR

(25% LEL)

ITEM	DESCRIPTION	COST $/YR	COST $/M SCF
RAW MATERIALS			
UTILITIES:			
COOLING WATER	$\$.03/10^{3}$ GAL.	–	
STEAM	$\$1.00/10^{3}$ LB	–	
NATURAL GAS	$\$.60/10^{6}$ Btu × $.0532 \times 10^{6}$ Btu/HR × 5840 HR/YR	185	
ELECTRICITY	$.015/KWH × 5 HP × .746 KW/HP × 5840 HR/YR	325	
MAINTENANCE:			
GENERAL MAINT.	5% CAPITAL COST (29,600)	1480	
MAINT. SUPPLIES		–	
DIRECT LABOR:	.5 HR/SHIFT × 730 SHIFT/YR × $4.00/HR	1460	
SUPERVISION:	10% DIRECT LABOR	146	
DIRECT MFG. COST		3596	
PAYROLL OVERHEAD	30% DIRECT LABOR	438	
PLANT OVERHEAD:	50% DIRECT LABOR	730	
PACKAGING:		–	
SHIPPING:		–	
INDIRECT MFG. COST		1168	
DEPRECIATION:	10% CAPITAL COST (30,050)	3005	
PROPERTY TAXES:	1% CAPITAL COST (30,050)	300	
INSURANCE:	0.5% CAPITAL COST (29,600)	148	
FIXED MFG COST		3453	
TOTAL PLANT LEVEL COST		8217	
CORPORATE OVERHEAD	3% TOTAL PLANT LEVEL COST	247	
TOTAL-MFG COST		8464	
	SAY	8,500	.0282

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MANUFACTURING ESTIMATE - OVEN EXHAUST CONTROL SCHEME

CONTROL PROCESS: THERMAL INCINERATION WITH PRIMARY HEAT RECOVERY OVEN EXHAUST RATE: 10,000 SCFM

PROCESS OPERATING TIME: 2 SHIFTS/DAY 365 DAYS/YR 5840 HR/YR

(25% LEL)

ITEM	DESCRIPTION	COST	
		$/YR	$/M SCF
RAW MATERIALS			
UTILITIES:			
COOLING WATER	$.03/10^3 GAL.		
STEAM	$1.00/10^3 LB		
NATURAL GAS	$.60/10^6 Btu × .532×10^6 Btu/HR × 5840 HR/YR	1850	
ELECTRICITY	$.015/KWH × 50HP × .746 KW/HP × 5840 HR/YR	3250	
MAINTENANCE:			
GENERAL MAINT.	5% CAPITAL COST (106,000)	5300	
MAINT. SUPPLIES		–	
DIRECT LABOR:	.5 HR/SHIFT × 730 SHIFT/YR × $4.00/HR	1460	
SUPERVISION:	10% DIRECT LABOR	146	
DIRECT MFG. COST		12,006	
PAYROLL OVERHEAD	30% DIRECT LABOR	438	
PLANT OVERHEAD:	50% DIRECT LABOR	730	
PACKAGING:		–	
SHIPPING:		–	
INDIRECT MFG. COST		1168	
DEPRECIATION:	10% CAPITAL COST (107,600)	10760	
PROPERTY TAXES:	1% CAPITAL COST (107,600)	1076	
INSURANCE:	0.5% CAPITAL COST (106,000)	530	
FIXED MFG COST		12,366	
TOTAL PLANT LEVEL COST		25,540	
CORPORATE OVERHEAD	3% TOTAL PLANT LEVEL COST	766	
TOTAL MFG COST		26,306	
	SAY	26,300	.0075

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MANUFACTURING ESTIMATE - OVEN EXHAUST CONTROL SCHEME

CONTROL PROCESS: THERMAL INCINERATION WITH PRIMARY HEAT RECOVERY ~ OVEN EXHAUST RATE: 20,000 SCFM (25% LEL)

PROCESS OPERATING TIME: 2 SHIFTS/DAY 365 DAYS/YR 5840 HR/YR

ITEM	DESCRIPTION	COST	
		$/YR	$/M SCF
RAW MATERIALS			
UTILITIES:			
COOLING WATER	$.03/10³ GAL.		
STEAM	$1.00/10³ LB		
NATURAL GAS	$.60/10⁶ Btu × 1.064×10⁶ Btu/HR × 5840 HR/YR	3700	
ELECTRICITY	$.015/KWH × 100 HP × .746 KW/HP × 5840 HR/YR	6500	
MAINTENANCE:		8550	
GENERAL MAINT.	5% CAPITAL COST (171,000)		
MAINT. SUPPLIES		—	
DIRECT LABOR:	.5 HR/SHIFT × 730 SHIFT/YR × $4.00/HR	1460	
SUPERVISION:	10% DIRECT LABOR	146	
DIRECT MFG. COST		20,356	
PAYROLL OVERHEAD:	30% DIRECT LABOR	438	
PLANT OVERHEAD:	50% DIRECT LABOR	730	
PACKAGING:		—	
SHIPPING:		—	
INDIRECT MFG. COST		1168	
DEPRECIATION:	10% CAPITAL COST (173,600)	17360	
PROPERTY TAXES:	1% CAPITAL COST (173,600)	1736	
INSURANCE:	0.5% CAPITAL COST (171,000)	855	
FIXED MFG COST		19951	
TOTAL PLANT LEVEL COST		41,475	
CORPORATE OVERHEAD	3% TOTAL PLANT LEVEL COST	1,244	
TOTAL MFG COST		42,719	
	SAY	42,700	.0061

MANUFACTURING ESTIMATE - OVEN EXHAUST CONTROL SCHEME

CONTROL PROCESS: THERMAL INCINERATION WITH SECONDARY HEAT RECOVERY - OVEN EXHAUST RATE: 1000 SCFM

PROCESS OPERATING TIME: 2 SHIFTS/DAY 365 DAYS/YR 5840 HR/YR

(25% LEL)

		COST	
ITEM	DESCRIPTION	$/YR	$/M SCF
RAW MATERIALS			
UTILITIES:			
COOLING WATER	$.03/$10^3$ GAL.	-	
STEAM	$ 1.00/10^3 LB	-	
NATURAL GAS	$ .60/10^6 Btu x .0532x10^6 Btu/HR x 5840 HR/YR	185	
ELECTRICITY	$.015/KWH x 10 HP x .746 KW/HP x 5840 HR/YR	650	
MAINTENANCE:			
GENERAL MAINT.	5% CAPITAL COST (40,000)	2000	
MAINT. SUPPLIES		-	
DIRECT LABOR:	.5 HR/SHIFT x 730 SHIFTS/YR x $4.00/HR	1460	
SUPERVISION:	10% DIRECT LABOR	146	
DIRECT MFG. COST		4441	
PAYROLL OVERHEAD:	30% DIRECT LABOR	438	
PLANT OVERHEAD:	50% DIRECT LABOR	730	
PACKAGING:		-	
SHIPPING:		-	
INDIRECT MFG. COST		1168	
DEPRECIATION:	10% CAPITAL COST (40,600)	4060	
PROPERTY TAXES:	1% CAPITAL COST (40,600)	406	
INSURANCE:	0.5% CAPITAL COST (40,000)	200	
FIXED MFG COST		4666	
TOTAL PLANT LEVEL COST		10,275	
CORPORATE OVERHEAD	3% TOTAL PLANT LEVEL COST	308	
TOTAL-MFG COST		10583	
	LESS	1295	
	NAT. GAS FUEL (SAVINGS @ OVEN) .368x10^6 x $.60/$10^6$ Btu x 5840 HR/YR = $1295/YR	9288	
	SAY	93.00	.033

MANUFACTURING ESTIMATE - OVEN EXHAUST CONTROL SCHEME

CONTROL PROCESS: THERMAL INCINERATION WITH SECONDARY HEAT RECOVERY ~ OVEN EXHAUST RATE: 10,000 SCFM (25% LEL)

PROCESS OPERATING TIME: 2 SHIFTS/DAY 365 DAYS/YR 5840 HR/YR

ITEM	DESCRIPTION	COST	
		$/YR	$/M SCF
RAW MATERIALS			
UTILITIES:			
COOLING WATER	$.03/$10^3$ GAL.		
STEAM	$1.00/$10^3$ LB		
NATURAL GAS	$ .60/10^6 Btu × .532×10^6 Btu/HR × 5840 HR/YR	1850	
ELECTRICITY	$.015/KWH × 100HP × .746 KW/HP × 5840 HR/YR	6500	
MAINTENANCE:			
GENERAL MAINT.	5% CAPITAL COST (147,000)	7350	
MAINT. SUPPLIES		-	
DIRECT LABOR:	.5 HR/SHIFT × 730 SHIFT/YR × $4.00/HR	1460	
SUPERVISION:	10% DIRECT LABOR	146	
DIRECT MFG. COST		17306	
PAYROLL OVERHEAD:	30% DIRECT LABOR	438	
PLANT OVERHEAD:	50% DIRECT LABOR	730	
PACKAGING:		-	
SHIPPING:		-	
INDIRECT MFG. COST		1168	
DEPRECIATION:	10% CAPITAL COST (149,200)	14920	
PROPERTY TAXES:	1% CAPITAL COST (149,200)	1,492	
INSURANCE:	0.5% CAPITAL COST (147,000)	735	
FIXED MFG COST		17,147	
TOTAL PLANT LEVEL COST		35,621	
CORPORATE OVERHEAD	3% TOTAL PLANT LEVEL COST	1068	
TOTAL-MFG COST		36,689	
	NATURAL GAS FUEL: (SAVINGS @ OVEN) LESS	12,950	
	3.68×10^6 Btu/HR × $.60/$10^6$ Btu × 5840 HR/YR = $12,950	23,739	
	SAY	23,700	.0068

Manufacturing Estimate - Oven Exhaust Control Scheme

Control Process: Thermal Incineration With Secondary Heat Recovery ~ Oven Exhaust Rate: 20,000 SCFM

Process Operating Time: 2 Shifts/Day 365 Days/Yr 5840 HR/YR (25% LEL)

Item	Description	Cost $/Yr	Cost $/M SCF
Raw Materials			
Utilities:			
Cooling Water	$.03/$10^3$ Gal.		
Steam	$1.00/$10^3$ LB		
Natural Gas	$.60/$10^6$ Btu × 1.064 × 10^6 Btu/Hr × 5840 Hr/Yr	3,700	
Electricity	$.015/KWH × 200 HP × .746 KW/HP × 5840	13,000	
Maintenance:		11,850	
General Maint.	5% Capital Cost (237,000)		
Maint. Supplies		—	
Direct Labor:	.5 HR/Shift × 730 Shift/Yr × $4.00/HR	1460	
Supervision:	10% Direct Labor	146	
Direct Mfg. Cost		30,156	
Payroll Overhead	30% Direct Labor	438	
Plant Overhead:	50% Direct Labor	730	
Packaging:		-	
Shipping:		-	
Indirect Mfg. Cost		1168	
Depreciation:	10% Capital Cost (240,600)	24060	
Property Taxes:	1% Capital Cost (240,600)	2406	
Insurance:	0.5% Capital Cost (237,000)	1185	
Fixed Mfg Cost		27,651	
Total Plant Level Cost		58,975	
Corporate Overhead	3% Total Plant Level Cost	1,769	
Total Mfg Cost		60,744	
	Less	25,900	
	Natural Gas Fuel: (Savings @ Oven) $7.36 \times 10^6 \frac{Btu}{Hr} \times \$.60/10^6 Btu \times 5840\ Hr/Yr = 25,900$	34,844	.0049
	Say	34,800	

8-93

RECEIVED
JUL 16 1971
Singmaster & Breyer, Inc.

July 15, 1971

Mr. Sam Martin
Singmaster & Breyer
235 East 42nd Street
New York, New York 10017

Dear Mr. Martin:

Confirming our telephone conversation, your design conditions are as follows:

Flow: 1000,10,000 and 20,000 SCFM
Temperature: 375°F
Contaminants: 50/50 mixture hexane and benzene
Concentration: 25% LEL
Fuel: Natural gas @ 60¢/10^6 BTU
Schedule: 80%
Performance: Rule 66, 90% conversion
Maximum Self-Recuperative Exchange: 46-47%
Correction Equipment: Thermal or Catalytic

As mentioned to you, the 1000 SCFM is too small for self-recuperative equipment and I hesitate to offer more than budget approximations on catalytic without a Cat 2 program run for sizing. By copy of this letter to Engineering with the appropriate request form, I am asking for this and will advise you as soon as it is complete.

Thermally we have the following:

1000 SCFM

Thermal unit only; Model RFA-30 Fumabator; about $9,000; size 4' wide by 4' high by 13' long @ 3200 lbs.; resistance to flow about 3" w.c. hot; specifications attached.

10,000 SCFM

Thermal unit only; Model DT-10,000-15.0M-SABH; about $30,000; size 8' wide by 8' high by 24' long @ 10,000 lbs.; resistance to flow 4-5" w.c. hot; specifications attached.

10,000 SCFM, Con't.

Thermal unit with self-recuperative heat exchanger; Model DT/SR-10,000-15.0M-SABH; about $47,500; size 8' wide by 8' high by 34' long @ 21,000 lbs.; resistance to flow 10-12" w.c. hot; specifications attached (same as thermal unit only specs).

20,000 SCFM

Thermal unit only; Model DT-20,000-15.0M-SABH; about $43,000; size 10' wide by 10' high by 24' long @ 14,000 lbs.; resistance to flow 4-5" w.c. hot; specifications attached (same specs as for 10,000 unit).

Thermal unit with self-recuperative heat exchanger; Model DT/SR-20,000-15.0M-SABH; about $75,500; size 10' wide by 10' high by 34' long @ 31,000 lbs.; resistance to flow 10-12" w.c. hot; specifications attached (same specs as for 10,000 unit).

Exhaust temperature on the self-recuperative units is about 900-1000°F.

I would budget about 50% on a grass roots for installation and 100% on a retrofit.

Very truly yours,

August 9, 1971

Mr. S. T. Martin
Singmaster & Breyer
235 East 42 Street
New York, NY 10017

Dear Mr. Martin:

During our recent telephone discussion, I indicated that I would forward information requested in your letter of July 15. At that time, I had not completely reviewed the data and conditions stated.

The LEL is hypothetically stated as 25% in air. We would be normally quoting only thermal oxidation equipment with a single pass heat exchanger (45%) in the two larger sizes. The price for these three models would be approximately $10,000, $50,000 and $70,000. The respective fuel useage would be as follows: 1.0 MMBTU/HR, 3.0 MMBTU/HR and 6.0 MMBTU/HR.

Many baking applications have contaminant in the range of 5 to 15% LEL. In this case, catalyst oxidation can be the more practical solution.

In as much as the above does not offer comparative data, you may wish to contact me for some other conditions of operation.

Very truly yours,

RECEIVED
AUG 11 1971
Singmaster & Breyer, Inc.

B-96

August 13, 1971

Mr. S. T. Martin
Singmaster & Breyer
235 East 42 Street
New York, NY 10017

Dear Mr. Martin:

Enclosed is a revision in our analysis for the project operating conditions described in your July 15 letter.

We are now basing our evaluations on 15% LEL. It should be noted that the catalyst can presently be replaced for approximately $1.00 per SCFM ($1,000, $10,000, and $20,000 respectively). I would anticipate 15,000 hours of operationas life from the process as described (50/50 by weight blend Hexane/Benzene).

Very truly yours,

RECEIVED
AUG 16 1971
Singmaster & Breyer, Inc.

Singmaster and Breyer
EPA Contract EHSD-71-12

Table 1 - Thermal Oxidation Units

SCFM		Without HX	With HX (45%)
1,000	Fuel	1.0 MMBTU/HR	
	Price	$10,000	
10,000	Fuel	10.0 MMBTU/HR	4.0 MMBTU/HR
	Price	$20,000	$50,000
20,000	Fuel		8.0 MMBTU/HR
	Price		$70,000

Table 2 - Catalytic Oxidation Units

SCFM		Without HX	With HX (45%)
1,000	Fuel	0.4 MMBTU/HR	
	Price	$11,000	
10,000	Fuel	4.0 MMBTU/HR	1.0 MMBTU/HR
	Price	$30,000	$60,000
20,000	Fuel		2.0 MMBTU/HR
	Price		$90,000

Conditions are 15% LEL; 375°F inlet; 1,000°F and 1,400°F.

8-13-71
FRE

*(1) FUEL CONSUMPTION FIGURES 15-30% GREATER THAN ADIABATIC
PER TELECON - 8/18/71 F.R. EDWARDS

(2) FAN COST INCLUDED IN BUDGET PRICES
HP FROM 5-50 FOR SMALLEST TO LARGEST UNIT

RECEIVED
SEP 13 1971
Singmaster & Breyer, Inc.

September 10, 1971

Mr. Sam Martin
Singmaster & Breyer
235 East 42nd Street
New York, New York 10017

25% LEL CATALYTIC COMBUSTION
50/50 - HEXANE/BENZENE

Dear Sam:

Confirming our conversations and further to our letter of July 15, this is a real toughie catalytically, partically due to the solvent composition and concentration. In fact, it would be hard to choose a more difficult combination as evidenced by the attached copies of our Cat 5 computer runs, and represents between 7 and 8 times the quanity of catalyst necessary for easy solvents like toluene or xylene, etc.

Now, summaring the budget costs reported to you, we have as follows:

Flow SCFM	Cat Unit	With Exchanger
1,000	$ 15,000	
10,000	$ 96,500	$107,500
20,000	$178,000	$201,000

and you have the fuel consumption, resistance to flow numbers, etc. In addition, the incinerator units to handle the solvent recovery waste gaseous vents specified are summarized as follows:

Flow SCFM	Flame Unit
1,000	$ 8,000
10,000	$11,000
20,000	$15,000

and only pilot fuel is necessary to ignite the mixture with excess air for complete combustion of the solvent laden steam.

Yours very truly,

8-99

Singmaster & Breyer

```
ON AT 11:33:01  20 JUL 71  TUESDAY    CSN80V   137
ASSISTANCE:  914-592-4851
USER ID,PASSWORD,PROJECT ID--DAL001,UOPROD

SYSTEM--BASIC
VERSION 14 JUN 71  12:39
READY
LOAD CAT5
READY
RUN

CAT5     11:35     07/20/71

ENTER CONVERSION,C,%; INLET TEMPERATURE, T1, DEGREES F;
AVG GAS FLOW, G, SCFM.
?90,600,1000

IF YOU WANT THE SOLVENT CODE PRINTED, ENTER 1; IF NOT, 0?0

ENTER SOLVENT CODE NUMBERS. USE ZEROS TO MAKE 8 ENTRIES
?14,1,0,0,0,0,0,0

ENTER CONCENTRATIONS, Y(N), BTU/SCF.  USE 0'S TO MAKE 8 ENTRIES
?6.7,6.42,0,0,0,0,0,0


INLET TEMPERATURE, TI = 600
OUTLET TEMPERATURE, TO= 1225
DELTA T               = 625


COMPONENT CONCENTRATIONS AT 5 POSITIONS IN BED FOLLOW

        Y(1)     Y(2)     Y(3)     Y(4)     Y(5)     Y(6)     Y(7)     Y(8)     X
        -----    -----    -----    -----    -----    -----    -----    -----    -----
J=1     6.66     4.17      .00      00       .00      .00      .00      .00      .23
J=2     6.49     1.86      .00      .00      .00      .00      .00      .00      .49
J=3     5.76      .22      .00      .00      .00      .00      .00      .00      .94
J=4     3.68      .00      .00      .00      .00      .00      .00      .00     1.66
J=5     1.30      .00      .00      .00      .00      .00      .00      .00     2.50

                   COMPONENT            CONVERSION
                   ----------           ----------
   1            14 N HEXANE               80.59
   2             1 BENZENE                ******
                   ----------           ----------
                     TOTAL                90.00
 CATALYST VOLUME =   13173.1


 FOR D2 CATALYSTS, THE FACE VELOCITY IS   25.6 FPM AT 70 F

             CAT SPEC        NUMBER          VELOCITY
             --------       --------         --------
              D 2              13              25.6
              D 3               9              38.5
              D 4               7              51.3
NOW AT END
```

B-100

```
ON AT 14:02:52  20 JUL 71  TUESDAY    CSN80V   145
ASSISTANCE:  914-592-4851
USER ID,PASSWORD,PROJECT ID--DAL001,UOPROD

SYSTEM--BASIC
VERSION 14 JUN 71  12:30
READY
LOAD CAT5
READY
RUN

CAT5      14:04      07/20/71

ENTER CONVERSION,C,%; INLET TEMPERATURE, T1, DEGREES F;
AVG GAS FLOW, G, SCFM.
?90,600,10000

IF YOU WANT THE SOLVENT CODE PRINTED, ENTER 1; IF NOT, 0?0

ENTER SOLVENT CODE NUMBERS. USE ZEROS TO MAKE 8 ENTRIES
?14,1,0,0,0,0,0,0

ENTER CONCENTRATIONS, Y(N), BTU/SCF.  USE 0'S TO MAKE 8 ENTRIES
?6.7,6.42,0,0,0,0,0,0


INLET TEMPERATURE, TI = 600
OUTLET TEMPERATURE, TO= 1225
DELTA T               = 625


COMPONENT CONCENTRATIONS AT 5 POSITIONS IN BED FOLLOW

       Y(1)    Y(2)    Y(3)    Y(4)    Y(5)    Y(6)    Y(7)    Y(8)    X
       -----   -----   -----   -----   -----   -----   -----   -----   -----
J=1    6.66    4.17     .00     .00     .00     .00     .00     .00     .23
J=2    6.49    1.86     .00     .00     .00     .00     .00     .00     .49
J=3    5.76     .22     .00     .00     .00     .00     .00     .00     .94
J=4    3.68     .00     .00     .00     .00     .00     .00     .00    1.66
J=5    1.30     .00     .00     .00     .00     .00     .00     .00    2.50

                     COMPONENT            CONVERSION
                    ----------            ----------
  1              14 N HEXANE                90.50
  2               1 BENZENE                 ******
                    ----------            ----------
                       TOTAL                90.00
 CATALYST VOLUME =  131731.3


 FOR D2 CATALYSTS, THE FACE VELOCITY IS   27.3 FPM AT 70 F
```

5-101

```
                --------         --------         --------
                D 2              **                   27.3
                D 3              82                   41.9
                D 4              61                   54.6
NOW AT END

14:09   RAN 0 MINS  0.54 SECS

READY
RUN

CAT5     14:10     07/20/71

ENTER CONVERSION,C,%; INLET TEMPERATURE, T1, DEGREES F;
AVG GAS FLOW, G, SCFM.
?90,600,20000

IF YOU WANT THE SOLVENT CODE PRINTED, ENTER 1; IF NOT, 0?0

ENTER SOLVENT CODE NUMBERS. USE ZEROS TO MAKE 8 ENTRIES
?14,1,0,0,0,0,0,0

ENTER CONCENTRATIONS, Y(N), BTU/SCF.  USE 0'S TO MAKE 8 ENTRIES
?6.7,6.42,0,0,0,0,0,0


INLET TEMPERATURE, TI = 600
OUTLET TEMPERATURE, TO= 1225
DELTA T               = 625


COMPONENT CONCENTRATIONS AT 5 POSITIONS IN BED FOLLOW


        Y(1)   Y(2)   Y(3)   Y(4)   Y(5)   Y(6)   Y(7)   Y(8)   X
        -----  -----  -----  -----  -----  -----  -----  -----  -----
J=1     6.66   4.17    .00    .00    .00    .00    .00    .00    .23
J=2     6.49   1.86    .00    .00    .00    .00    .00    .00    .49
J=3     5.76    .22    .00    .00    .00    .00    .00    .00    .94
J=4     3.68    .00    .00    .00    .00    .00    .00    .00   1.66
J=5     1.30    .00    .00    .00    .00    .00    .00    .00   2.50

                    COMPONENT         CONVERSION
                    ----------        ----------
    1            14 N HEXANE            80.59
    2             1 BENZENE             ******
                    ----------        ----------
                      TOTAL             90.00
  CATALYST VOLUME =   253452.6


  FOR D2 CATALYSTS, THE FACE VELOCITY IS   27.3 FPM AT 70 F

                CAT SPEC         NUMBER           VELOCITY
                --------         --------         --------
                D 2              **                   27.3
                D 3              **                   41.9
                D 4              **                   54.6
NOW AT END

14:14   RAN 0 MINS  0.25 SECS
```

```
READY
OFF


OFF AT 14:14
ELAPSED PROCESSOR TIME.. 0 MINS  0.91 SECS
ELAPSED TERMINAL TIME... 12 MINS




 FILES SAVE
```

APPENDIX C

CALCULATIONS, QUOTES AND CORRESPONDENCE

ADSORPTION

TABLE OF CONTENTS

CONTROL PROCESS CONCEPT C-1
ADSORPTION PROCESS CALCULATIONS C-2
INSTALLED CAPITAL COST ESTIMATES C-23
OPERATING COST ESTIMATES C-38
ADSORPTION ISOTHERMS C-53
VENDOR BUDGET QUOTATIONS C-58

PROCESS CONCEPT FOR CONTROL OF HEXANE AND BENZENE FUMES FROM A PAINT BAKING OVEN VIA ADSORPTION WITH SOLVENT RECOVERY OR INCINERATION

A paint baking oven exhausts a 50/50 weight percent mixture of benzene and benzene vapors in air at a temperature of 375°F and at concentrations of 15% and 25% of the lower explosive limit (LEL).

An economic evaluation of adsorption-recovery and adsorption-incineration with and without heat recovery control systems is performed for oven exhaust volumes of 1,000, 10,000 and 20,000 SCFM. Disposal (sewerage) costs of the small amount (less than 5 gpm) of waste water were not included. These costs would be small and would not affect the overall magnitude of the estimated operating costs.

The system's basis of evaluation is at 90% recovery or conversion of emissions. The oven is assumed to operate 2 shifts per day and 365 days per year.

In addition, an economic evaluation of adsorption and incineration without heat recovery is developed for an oven exhaust solvent concentration of 200 ppm under the same conditions outlined above.

SINGMASTER & BREYER

CHEMICAL & METALLURGICAL PROCESS ENGINEERS

COMPUTATION SHEET

J. O. No. PS-228

SHEET No. C-2 OF

NAME OF COMPANY MSA Research Corp

DATE 7/22/71

SUBJECT Adsorption/Solvent Recovery/Incineration Study COMP. BY STM C'K'D BY

Basis of Evaluation

A paint baking oven exhausts a 50/50 mixture by weight of hexane & benzene at 25% Lower Explosive Limit (LEL). Concentration in air at 375°F. 95% by weight of the hydrocarbon mixture is to be adsorbed for future disposition as follows: 1) Recovery & reuse as a paint thinner in the process 2) disposed of by incineration when the hydrocarbons thermally degrade through reuse. 95% conversion of hydrocarbons to H_2O and CO_2 required by incinerator.

Evaluate the process requirements of adsorption & recovery and adsorption & thermal incineration with & without heat recovery at capacities of 1000, 10,000, and 20,000 SCFM

Physical Data

LEL: Benzene = 1.5% in air by volume
Hexane = 1.2% in air by volume
} L.E.L. Values from Ch.E. Handbook 3rd Ed. p 1868

Adsorber Capacity, (SCFM)	1000	10,000	20,000
Carbon Charge/Adsorber, (LBS)	2,800	24,000	40,000

Working Capacity Carbon - 10 LB hydrocarbon/100 LB carbon

Steam Regeneration Requirement - 2.5 - 3.5 LB steam/LB hydrocarbon
Assume 3.0 LB/LB

Life of Carbon - 5 yrs

Blower HP (per Vulcan Cincinnati Quote)	15	75	125

Cooling Water - Assume 15°F Rise say 80-95°F

SINGMASTER & BREYER
CHEMICAL & METALLURGICAL PROCESS ENGINEERS

COMPUTATION SHEET

J. O. No. PS-228

SHEET No. C-3 OF

NAME OF COMPANY MSA RESEARCH CORP

DATE 7/22/71

SUBJECT ADSORPTION/SOLVENT RECOVERY/INCINERATION STUDY

COMP. BY STM C'K'D BY

PHYSICAL DATA (CON'T)

COMPOUND	VAPOR AVG SP. HT., (Btu/lb°F)	BOILING POINT, °F	LATENT HEAT VAPORIZATION, (Btu/LB)
HEXANE	.75	157	145
BENZENE	.60	176	170
OXYGEN	.24	–	–
NITROGEN	.26	–	–
CARBON DIOXIDE	.25	–	–
WATER VAPOR	.50	212	970
AIR	.26	–	–

AVG C_p (Btu/lb°F) LIQUID = HEXANE = .527 BENZENE = .46

COMBUSTION REACTION DATA

COMPOUND	HEAT OF COMBUSTION, (Btu/lb)	CHEMICAL REACTION
HEXANE	19,391	$C_6H_{14} + 9.5O_2 \rightarrow 6CO_2 + 7H_2O\uparrow$
		MW → 86 304 264 126
BENZENE	17,446	$C_6H_6 + 7.5O_2 \rightarrow 6CO_2 + 3H_2O$
		MW → 78 240 264 54
METHANE	21,502	$CH_4 + 2O_2 \rightarrow CO_2 + 2H_2O$
		MW → 16 64 44 36

ADSORPTION WITH SOLVENT RECOVERY

ENERGY &
MATERIAL BALANCE: BASIS 1000 SCFM OVEN EXHAUST

AV. MOL. WT. HEXANE/BENZENE MIX = 82

1/4 LEL ~ 3 FT^3 SOLV. VAP / 997 FT^3 AIR

$\frac{3}{359} \times 82 \times \frac{492}{520} \times 60 = 38.8$ LB/HR SOLVENT

SOLVENT ADSORBED / RECOVERED = .95 (38.8) = 37.0 LB/HR

SINGMASTER & BREYER
CHEMICAL & METALLURGICAL PROCESS ENGINEERS

COMPUTATION SHEET
J. O. No. PS-228
SHEET No. C-4 OF
DATE 7/22/71
COMP. BY STM C'K'D BY

NAME OF COMPANY MSA RESEARCH CORP
SUBJECT ADSORPTION WITH SOLVENT RECOVERY - STUDY

CARBON BED:

2800 (.10) = 230 LB SOL. ADSORPED/BED

$\frac{280}{37}$ = 7.58 HR ABS. TIME.

280 LB. SOLV. × 3 $\frac{\text{LB STEAM}}{\text{LB SOLV}}$ = 840 LB STEAM/BED

ASSUME: STEAM REGENERATION TIME ≃ 6/7 CYCLE = 6.50 HR
COOLING & DRYING ~ 1/7 CYCLE = 1.08 HR

INST STEAM DEMAND = 129 LB/HR INST. SOLV. RATE = $\frac{280}{6.5}$ = 43.1 $\frac{\text{LB}}{\text{HR}}$
AVG STEAM DEMAND = 111 LB/HR

VAPOR/AIR PRECOOLER

COOLING WATER:

$$\Delta H_{\substack{\text{AIR}\\\text{STREAM}}} = [(.75)(19.4) + (.60)(19.4) + (.26)(4560)][375-100]$$
$$= (14.6 + 11.6 + 1190)(275) = 1216.2\,(275) = 334000 \text{ Btu/hr}$$

$$\Delta H_{\text{C.W}} = 8.34\,(15) = 125 \text{ Btu/GAL}$$

COOLING WATER (GPH) = 334000/125 = 2675 GPH

CONDENSER:

ASSUME: LOW PRESSURE STEAM USED DURING REGENERATION ENTERS THE CONDENSER SATURATED AT 212°F & ALL PRODUCTS LEAVE SUB-COOLED @ 100°F & THAT THE SOLUBILITIES GIVEN BELOW ARE APPROXIMATELY THE SAME @ 100°F

	SOLUBILITY IN WATER
BENZENE	7% @ 71°F
HEXANE	1.4% @ 60°F

SINOMASTER & BREYER
CHEMICAL & METALLURGICAL PROCESS ENGINEERS

COMPUTATION SHEET
J. O. No. PS-228
SHEET No. C-18 OF
DATE 7/23/71
COMP. BY STM C'K'D BY

NAME OF COMPANY MSA RESEARCH CORP
SUBJECT ADSORPTION WITH SOLVENT RECOVERY - STUDY

CONDENSER (CONT)

$$\Delta H_{\text{RECOVERY}} = 21.55[(.75)(212-157) + 145 + (.53)(157-100)] + 21.55[(.6)(212-176) + 170 + .46(176-100)]$$

$$+ 129[(970) + 1(212-100)]$$

$$= 21.55[41.3 + 145 + 30.2 + 21.6 + 170 + 34.9] + 126,500 + 15,500$$

$$= 9570 + 107,000 + 12,300 = 128,870 \text{ Btu/hr}$$

COOLING WATER REQUIREMENT

$$\frac{128,870}{8.34(15)} = 1630 \text{ GPH(INST)}$$

SOLVENT RECOVERED: (INST RATE)

$21.55 - .07(129) = 12.50$ LB/HR BENZENE
$21.55 - .014(129) = 19.74$ LB/HR HEXANE

AVG RATE SOLV. RECOVERED:
BENZENE = 10.7 LB/HR ; HEXANE = 16.9 LB/HR

SUMMARY - 1000 SCFM ADSORBER & SOLVENT RECOVERY (AVG RATES)

STEAM - 111 LB/HR   COOLING WATER - 3560 GPH

SOLVENT RECOVERED: 10.7 LB/HR BENZENE
16.91 LB/HR HEXANE

ESTIMATE: VAPOR-AIR PRECOOLER
OVERALL HEAT TRANSFER COEFFICIENT - $U = 2-10$ USE $U = 6$

$$\Delta T_{lm} = \frac{280-20}{\ln \frac{280}{20}} = \frac{260}{2.65} = 98$$

1000 SCFM: $\frac{q}{U \Delta T_{lm}} = A = \frac{334,000}{6 \times 98} = 570 \text{ FT}^2$

10,000 SCFM: $A = 5700 \text{ FT}^2$
20,000 SCFM: $A = 11,400 \text{ FT}^2$

*INSTALLED COST ~ 1.71 M-S. INDEX ADJUSTMENT
1000 - 1.71 (3300) = \$ 5650

10000 - 1.71 (13,000) = \$ 22,250

20000 - 1.71 (25,000) = \$ 42,750

*EQUIPMENT PRICES FROM: CHEMICAL ENGINEERING COST ESTIMATION, McGRAW-HILL

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COMPUTATION SHEET
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SHEET No. C-6 OF
DATE 7/23/71
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NAME OF COMPANY MSA RESEARCH CORP.
SUBJECT ADSORPTION WITH SOLVENT RECOVERY - STUDY

SUMMARY - PROCESS RATES & COSTS

ADSORBER CAPACITY, (SCFM)	1,000	10,000	20,000
STEAM RATE, (LB/HR) AVG	110	1110	2220
COOLING WATER RATE, (GPH) AVG	3550	35600	71,200
SOLVENT RECOVERY RATE, (LB/HR) AVG			
BENZENE:	10.75	107.5	214
HEXANE:	16.91	1691	338
PRICE/LB BENZENE	$ .0300		
HEXANE	$ .0375		
ACTIVATED CARBON	$ .50		
BLOWER HP	15	75	125
ACTIVATIVATED CARBON CHARGE/SYSTEM	5,600	48,000	80,000

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COMPUTATION SHEET

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NAME OF COMPANY MSA RESEARCH CORP
SUBJECT ADSORPTION WITH INCINERATION - STUDY

ESTIMATED PRICE ADJUSTMENT - FOR - QUOTE FOR DELETION OF OF CONDENSER & DECANTER

CONDENSER -

$$\Delta T_{lm} : \frac{117-20}{\ln \frac{117}{20}} = \frac{97}{1.76} = 55\,^{\circ}F$$

$$\underset{\substack{\text{COND}\\ \text{STEAM - WATER}}}{U} = 150-800, \quad U_{s/w} = 475$$

$$\underset{\substack{\text{COND}\\ \text{ORGANIC VAPOR - } H_2O}}{U} = 60-300 \quad U_{o/w} = 180$$

$$U_{mean} = .75(475) + .25(180)$$
$$\cong 400 \text{ Btu/hr ft}^2\,^{\circ}F$$

1000 SCFM

$$A = \frac{q}{U\Delta T_{lm}} = \frac{128{,}870}{400(55)} = 5.8 \text{ ft}^2$$

\$350(1.71) = \$600

10,000 SCFM

58 Ft^2

\$900(1.71) = \$1540

20,000 SCFM

116 Ft^2

\$1300(1.71) = \$2230

DECANTER -

- ASSUME 1 HR DWELL TIME

1000 SCFM

1000 SCFM (30 GAL) = 1.71(200) = \$350

$$C_6H_6 = \frac{21.55}{8.34(.88)} = 2.95$$

10,000 SCFM (300 GAL) = 1.71(620) = \$1060

$$C_6H_{14} = \frac{21.55}{8.34(.66)} = 3.92$$

20,000 SCFM (550 GAL) = 1.71(900) = \$1540

$$H_2O = \frac{129}{8.34} = \frac{15.40}{22.27} \times 1.2 = 26.7$$

SAY 25 GAL

TOTAL DEDUCT - EQUIP + 50% FOR PIPING

1000 SCFM = \$1425 10,000 SCFM = \$3900 20,000 SCFM = \$5660

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COMPUTATION SHEET
J. O. No. PS-228
SHEET No. C-9 OF
DATE 8/24/71
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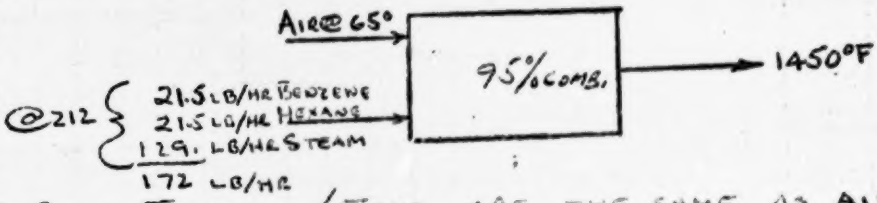
NAME OF COMPANY MSA Research Corp
SUBJECT Adsorber with Incinerator ~ No Heat Recovery

BASIS: 1000 SCFM EXHAUST


Air @ 65°
95% comb.
1450°F
@ 212
21.5 lb/hr Benzene
21.5 lb/hr Hexane
129. lb/hr Steam
172 lb/hr

Assume: SCFM Cond. Exhaust/Feed are the same as Air

$C_P = .26$ Btu/lb °F
$\rho = .076$ lb/ft³

Feed:
Heat of Comb. – $\left(\frac{17{,}446 + 19{,}391}{2}\right)(43)(.95) = 773{,}000$ Btu/hr

① Assume feed blend @ 100°F & rise @ 1350°F

$$\frac{773{,}000}{.26\,(1350)} = 2200 \text{ lb/hr}$$

Check – 2200 − 172 = 2028 lb/hr Air

$$172(.54)(212-T) = 2028(.26)(T-65)$$
$$93(212-T) = 530(T-65)$$
$$212-T = 5.7T - 370$$
$$T = \frac{582}{6.7} = 87$$
$$1450 - 87 = 1363\,°F$$

Cp Avg. Feed:

	Cp	×	Wt Frac	
Benzene	.60	×	.125	.075
Hexane	.75	×	.125	.094
H_2O	.50	×	.75	.375
				.544 Btu/lb

	Wt Frac		Cp	
2028	.92	×	.26	.24
172	.08	×	.54	.04
2200			$C_{P_{AV}}$ =	.28

$$\frac{773{,}000}{.28\,(1363)} = 2030$$

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COMPUTATION SHEET
J. O. No. PS-228
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SUBJECT Adsorber with Incinerator ~ No Heat Recovery
COMP. BY STM C'K'D BY

② Assume Feed @ 90°F & Rise @ 1360°F, $C_p = .28$

$$\frac{773{,}000}{.28\,(1360)} = 2030 \text{ LB/HR}$$

CHECK

$2030 - 172 = 1858$ LB/HR AIR

		WT FRAC		C_p		
AIR	1858	.92	×	.26	=	.238
FEED	172	.08	×	.54	=	.043
	2030					.281 Btu/Lb°F

$172(.54)(212-T) = 1858(.26)(T-65)$

$93(212-T) = 483(T-65)$

$212 - T = 5.2T - 337$

$T = \frac{549}{6.2} = 89$

SCFM/1000 SCFM OVEN EXHAUST

Solv $\frac{43}{92}\times\left(\overset{6.32}{\frac{359}{\cancel{60}}\times\frac{520}{492}}\right) = 3.32$ SCFM

$H_2O\uparrow$ $\frac{129}{18}\times 6.32 = 45.30$ "

AIR $\frac{1858}{29}\times 6.32 = 405.00$ "

453.62 SCFM

OVEN EXHAUST RATE, SCFM	1000	10,000	20,000
INCINERATOR FEED RATE, SCFM	454	4540	9080
FUEL CONSUMPTION	–	–	–

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SUBJECT Adsorption with Incineration - Study
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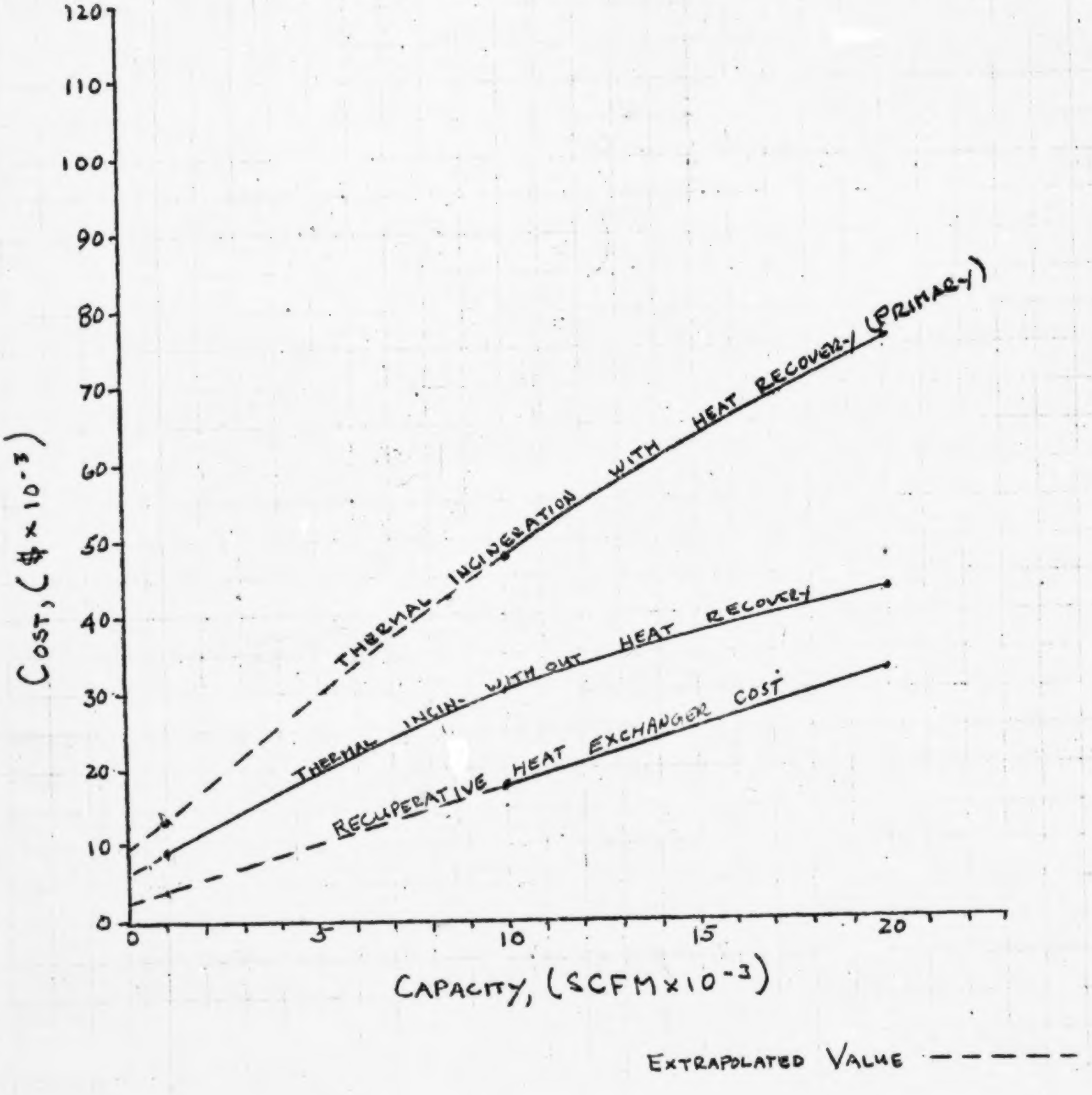
PLOT OF QUOTES: THERMAL INCINERATION WITH & WITHOUT RECOVERY
(SOURCE: BUDGET/ QUOTES)
25% LEL - HEXANE/BENZENE



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COMPUTATION SHEET
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NAME OF COMPANY MSA RESEARCH CORPORATION

SUBJECT ADSORPTION WITH INCINERATION - STUDY

INCINERATION BALANCE

1000 SCFM ADSORBER SYSTEM

$\frac{2800(.10)}{37}$ = 7.58 HR/CYCLE $\quad$ $\frac{6}{7}(7.58)$ = 6.50 HR STEAMING

$\frac{280}{6.5}$ = 43 LB/HR SOLV $\quad$ $\frac{280(3)}{6.5}$ = 129.0 LB/HR STEAM

10,000 SCFM ADSORBER SYSTEM

$\frac{24,000(.10)}{370}$ = 6.55 HR/CYCLE

$\frac{6}{7}(6.5)$ = 5.65 HR STEAMING

SOLVENT RATE ~ $\frac{2400}{5.65}$ = 430 $\frac{LB}{HR}$ $\quad$ STEAM RATE = $\frac{2400(3)}{5.65}$ = 1290 $\frac{LB}{HR}$

20,000 SCFM ADSORBER SYSTEM

$\frac{40,000(.10)}{740}$ = 5.4 HR/CYCLE

$\frac{6}{7}(5.4)$ = 4.65 HR STEAMING

SOLVENT RATE ~ $\frac{4000}{4.65}$ = 8601 $\frac{LB}{HR}$ $\quad$ STEAM RATE. $\frac{4000(3)}{4.65}$ = 2590 LB/HR

INCINERATOR RATE REQUIREMENT

	1000 SCFM SYSTEM	10,000 SCFM SYSTEM	20000 SCFM SYSTEM
HEXANE, (LB/HR)	21.5	215	430
BENZENE, (LB/HR)	21.5	215	430
STEAM, (LB/HR)	129.0	1290	2590

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CHEMICAL & METALLURGICAL PROCESS ENGINEERS

COMPUTATION SHEET
J. O. No. PS-228
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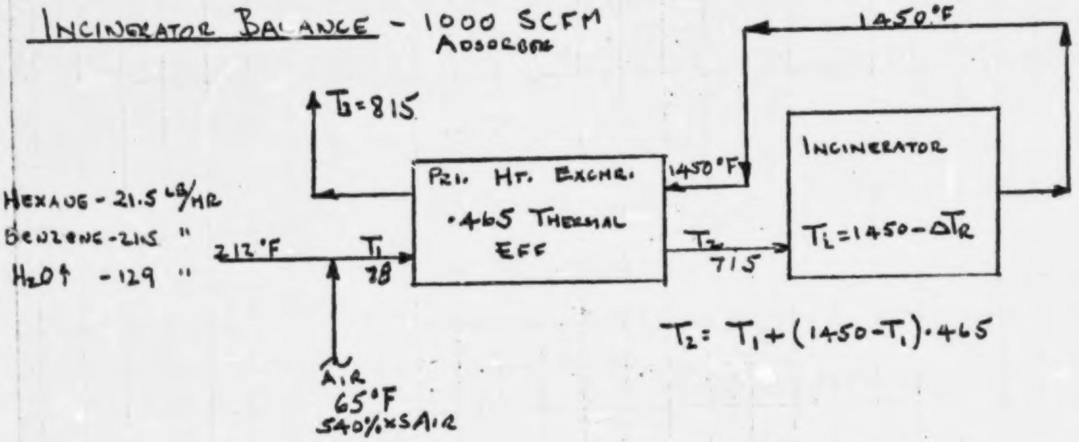
NAME OF COMPANY MSA RESEARCH CORPORATION
SUBJECT ADSORPTION WITH INCINERATION - STUDY
COMP. BY STM C'K'D BY

INCINERATOR BALANCE - 1000 SCFM ADSORBER



1450°F
T_3=815
PRI. HT. EXCHR.
.465 THERMAL EFF
1450°F
INCINERATOR
T_i=1450−ΔTR
HEXANE - 21.5 LB/HR
BENZENE - 21.5 "
H_2O↑ - 129 "
212°F
T_1
78
T_2
715
AIR
65°F
540% XS AIR

$$T_2 = T_1 + (1450 - T_1) .465$$

FIND MIN. AIR DILUTION FOR ZERO FUEL REQUIREMENT
IE $T_i = T_2$

STOICH AMTS @ 95% COMB.

HEXANE $\frac{21.5}{86} \times 304 \times .95 = 72.5$ LB/HR O_2 BENZENE $\frac{21.5}{78} \times 240 \times .95 = 63$ LB/HR O_2

$\frac{72.5}{32} \times \frac{79}{21} \times 28 = 238$ LB/HR N_2 $\frac{63}{32} \times \frac{79}{21} \times 28 = 208$ LB/HR N_2

STOICH. AIR = 581.5 LB/HR AIR

$CO_2 = \frac{264}{304} \times 72.5 + \frac{264}{240} \times 63 =$

$= 63 + 69.5 = 132.5$ LB/HR CO_2

$H_2O = \frac{126}{304} \times 72.5 + \frac{54}{240} \times 63$

$= 30 + 14.2 = 44.2$ LB/HR H_2O

AVG CP INLET GASES - STOICH AMOUNT

	LB/HR	WT FRACTION		CP	AVG CP
HEXANE	21.5	.0272	×	.75	.0204
BENZENE	21.5	.0272	×	.60	.0163
H_2O	129.0	.1710	×	.5	.0855
AIR	581.5	.7750	×	.26	.2010
	753.5	1.0014			.3232

AVG CP ADSORBER STREAM

	LB/HR	WT FRAC	CP	
HEX	21.5	.125	.75	.094
BEN	21.5	.125	.60	.075
H_2O	129.0	.750	.50	.375
	172.0	1.000		.544

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COMPUTATION SHEET
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NAME OF COMPANY MSA RESEARCH CORP
SUBJECT ADSORPTION WITH INCINERATION - STUDY

INCINERATOR BALANCE - 1000 SCFM ADSORBER

AVG C_P OUTLET GASES - STOICH. AMOUNT

	LB/HR	WT FRACTION		C_P	AVG C_P
HEXANE	1	.002	×	.75	.0015
BENZENE	1	.002	×	.60	.0012
CO_2	132.5	.176	×	.25	.044
H_2O	173.2	.229	×	.50	.115
N_2	446.0	.590	×	.26	.154
	753.7	.999			.3157~
					.316

HEAT OF COMBUSTION

$$\left(\frac{17{,}446+19{,}391}{2}\right)(43)(.95) = 773{,}000 \text{ Btu/Hr}$$

ASSUMPTION #1 - 300% XS AIR ~ (3 × 581.5 = 1744.5 lb/HR XS)

	LB/HR	WT FRAC	C_P	AVG C_P
OUTLET GAS	753.7	.302	.316	.0955
XS AIR	1744.5	.698	.26	.182
	2498.2			.278

$$\Delta T_a = \frac{773{,}000}{.278(2500)} = 1100°F$$

$T_i = 350$

$$T_1: \quad 172(.544)(212-T_1) = 2326(.26)(T_1-65)$$
$$93.5(212-T_1) = 605(T_1-65)$$
$$19800 - 93.5T_1 = 605T_1 - 39{,}250$$
$$T_1 = \frac{59{,}050}{698.5} = 84.5°F$$

$$T_2 = 84.5 + (1450 - 84.5).465 = 635 + 84.5 = 719.5$$

$$\therefore T_2 \neq T_i$$

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COMPUTATION SHEET
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SUBJECT ADSORPTION WITH INCINERATION - STUDY

ASSUMPTION #2 - 600% XS AIR ~ (6 × 581.5 = 3500 LB/HR XS)

	LB/HR	WT FRAC	CP	AV CP
OUTLET GAS	753.7	.177	.316	.056
XS AIR	3500.0	.823	.26	.215
	4253.7	1.000		.271

$\Delta T_R = \frac{773,000}{(.27)(4254)} = 675°F$

$T_i = 1450 - 675 = 775$

T_1: $19,800 - 93.5 T_1 = 4082(.26)(T_1 - 65)$

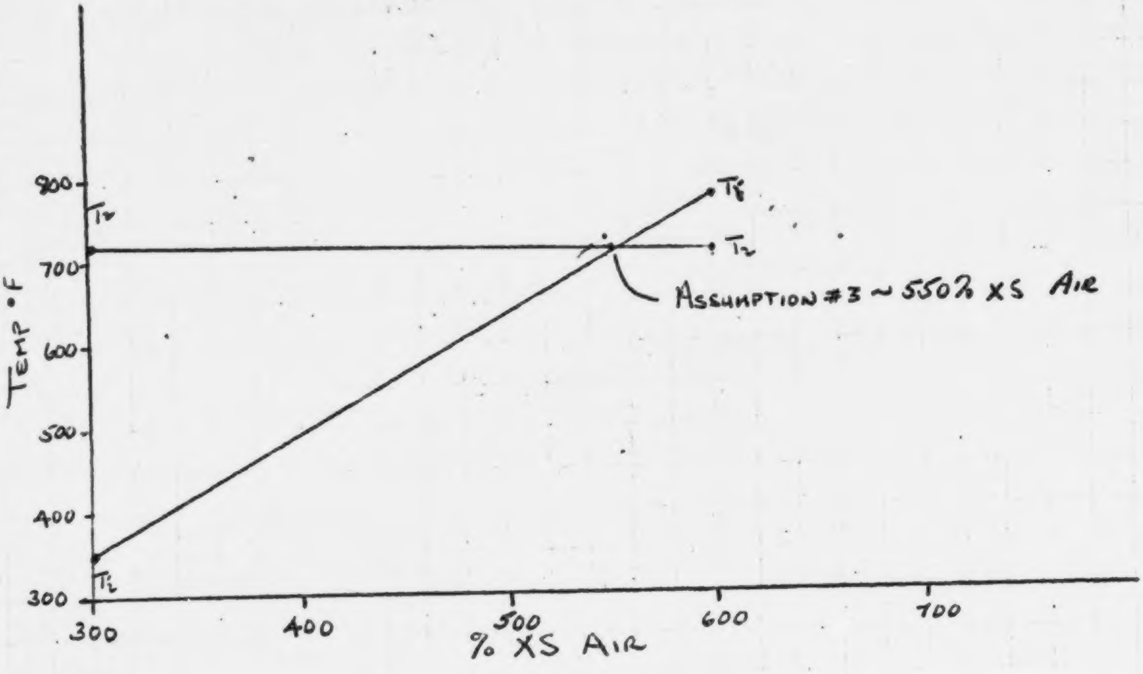
$19,800 - 93.5 T_1 = 1060 T_1 - 69,000$

$T_1 = \frac{88,800}{1154}$

$T_1 = 77$

$T_2 = 77 + (1450 - 77).465$

$= 77 + 638 = 715$



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COMPUTATION SHEET
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SHEET No. C-15 OF
DATE 7/26/71

NAME OF COMPANY MSA RESEARCH CORP.
SUBJECT ADSORPTION WITH INCINERATOR - STUDY
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ASSUMPTION #3 - 550% XS AIR ~ ($5.5 \times 581.5 = 3200$ LB/HR XS)

	LB/HR	WT. FRAC	CP	AVG CP
OUTLET GAS	753.7	.19	.316	.06
XS AIR	3200.0	.81	.26	.21
	3953.7			.27

$$\Delta T_R = \frac{773,000}{.27(3953)} = 723\ °F$$

$$T_i = 1450 - 723 = 727$$

$$T_1: \quad 19,800 - 93.5T_1 = 3781.5(.26)(T_1 - 65)$$

$$19,800 - 93.5T_1 = 982T_1 - 63,800$$

$$T_1 \quad \frac{83,600}{1076} = 78$$

$$T_2 = 78 + (1450 - 78).465 = 715$$

ASSUMPTION #4 - 540% XS AIR ~ ($5.4 \times 581.5 = 3140$ LB/HR XS)

	LB/HR	WT FRAC	CP	AVG CP
OUTLET GAS	753.7	.195	.316	.062
XS AIR	3140.0	.805	.26	.209
	3893.7	1.000		.271

$$\Delta T_R = \frac{773,000}{.27(3894)} = 735\ °F$$

$$T_i = 1450 - 735 = 715$$

$$T_1: \quad 19,800 - 93.5T_1 = 3721(.26)(T_1 - 65)$$

$$19800 - 93.5T_1 = 970\,T_1 - 63,000$$

$$1064\,T_1 = 82,800$$

$$T_1 = 78$$

$$T_2 = 78 + (1450 - 78)(.465) = 716°F \qquad \& \ T_i \cong T_2$$

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COMPUTATION SHEET
J. O. No. PS-228
SHEET No. C-16 OF
DATE 7/26/71
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NAME OF COMPANY MSA Research Corp

SUBJECT Adsorption with Incineration - Study

INCINERATOR FEED RATE - 1000 SCFM ADSORBER SYSTEM

SOLVENT $\frac{43}{82} \times \overset{6.32}{\left(\frac{359 \times 520}{\cancel{60} \quad 492}\right)} = 3.32$ SCFM

H_2O $\frac{129}{18} \times 6.32 = 45.30$

AIR $\frac{6.4\,(581.5)}{29} \times 6.32 = \frac{812.00}{860.62}$ SCFM Say 860 SCFM

Adsorber Capacity, (SCFM)	1000 SCFM	10,000	20,000
* Incinerator Capacity, (SCFM)	860	8600	17,200
Blower HP	5	50	100
Cooling Water, (GPH)	2675	26,750	53,500

* Incinerator costs taken from plot on page C-10

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COMPUTATION SHEET
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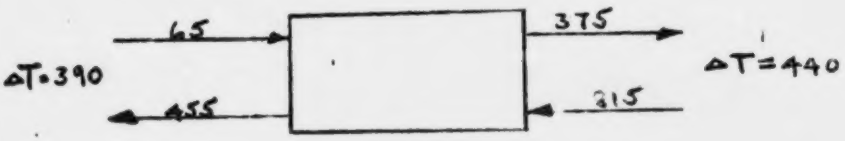
NAME OF COMPANY MSA RESEARCH CORP.
SUBJECT ADSORPTION WITH INCINERATION

ADSORPTION / INCINERATION & SECONDARY HEAT RECOVERY

BASIS: 1000 SCFM MAKE-UP



MAKE-UP

$$\frac{1000}{359}\times\frac{492}{520}\times 29\times 60 = 4575\ \frac{\text{LB}}{\text{HR}}\ \text{AIR}$$

EXHAUST

$$\frac{860}{1000}\times 4575 = 3940\ \text{LB/HR}$$

$$4575(\cancel{.29})(\overset{310}{\cancel{375-65}}) = 3940(\cancel{.29})(815-T)$$

$$360 = 815 - T$$

$$T = 455\text{°F}$$

$$\Delta T_{lm} = \frac{440-390}{\ln\frac{440}{390}} = \frac{50}{\ln 1.13} = \frac{50}{.123} = 405\text{°F}$$

$$q = 4575(.29)(310) = 410{,}000\ \text{Btu/Hr}$$

$$U = 5\ \text{Btu/Hr.Ft}^2\ \text{°F}$$

$$A = \frac{4.1\times10^5}{5\times 4.05\times10^2} = .203\times10^3 = 203\ \text{FT}^2$$

NOTE: METHOD FOR COSTING OUT SECONDARY HEAT EXCHANGER IS SAME AS THAT USED FOR INCINERATOR STUDY

MAKE-UP AIR RATE, SCFM	HEAT EXCHR. AREA	COST	INSTANT. Btu/Hr SAVED	AVG. Btu/HR SAVED
1000	203	5000	4.1×10^5	3.52×10^5
10000	2030	19000	4.1×10^6	3.52×10^6
20000	4060	28000	8.2×10^6	7.05×10^6

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Name of Company MSA Research Corp

Subject Adsorption/Incineration Study
(Trace Solvent Concentration w/ Catalyst Poison)

BASIS OF EVALUATION - ALTERNATE CASE

AN OVEN EXHAUSTS A 50/50 MIXTURE BY WEIGHT OF HEXANE/BENZENE IN AIR AT A TEMPERATURE AND CONCENTRATION OF 375°F AND 200 PPM RESPECTIVELY. CATALYTIC INCINERATION CAN NOT BE USED AS AN EMMISION CONTROL METHOD BECAUSE OF TRACE AMOUNTS OF CATALYST POISON PRESENT IN THE EXHAUST.

EVALUATE THE PROCESS REQUIREMENTS FOR ADSORPTION/THERMAL INCINERATION SYSTEMS NECESSARY TO REDUCE EMMISION LEVELS BY 90% AT OVEN EXHAUST RATES OF 1000, 10,000, AND 20,000 SCFM.

PHYSICAL DATA

ADSORBER CAPACITY, (SCFM)	1,000	10,000	20,000
*ACTIVATED CARBON CHARGE/ ADSORBER, LBS	930	8000	13,300
WORKING CAPACITY - CARBON	10 LB SOLVENT/100 LB CARBON		
CARBON LIFE	5 YRS.		
BLOWER HP (PER BUDGET QUOTE)	15	75	125
COOLING WATER	ASSUME 15°F RISE SAY		

*MIN. CHARGE FOR MINIMUM BED DEPTH BASED ON VENDOR'S DESIGN

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COMPUTATION SHEET
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NAME OF COMPANY MSA RESEARCH CORP

SUBJECT ADSORPTION/INCINERATION STUDY
(TRACE SOLVENT W/ CATALYST POISON)

BASIS: 1000 SCFM OVEN EXHAUST

CONC.
200 PPM ~ .2 LB. SOLV/1000 LB AIR

$$\text{DENSITY}: \sim \frac{1000.2}{\left(\underset{=0}{\cancel{\frac{.2}{82}}} + \frac{1000}{29}\right) 359 \times \frac{520}{492}} = \frac{1000.2}{13{,}100} = .0763 \text{ LB/FT}^3$$

SOLVENT RATES:

$$.0763\,(1000)(60) \times \frac{.2}{1000} = .915 \text{ LB/HR}$$

@95% ADSORPTION EFFICIENCY LOADING RATE = .87 LB/HR

CARBON LOADING CAPACITY		LOADING TIME
1000 SCFM UNIT:	93 LB SOLV.	107 HR
10,000 SCFM UNIT:	800 "	92 HR
20,000 SCFM UNIT	1330 "	76.5 HR

AVG STEAM RATE REQUIREMENT

1000 SCFM UNIT ~ $\frac{3 \times 93}{107} = 2.61$ LB/HR

10,000 SCFM UNIT ~ $\frac{3 \times 800}{92} = 26.1$ LB/HR

20,000 SCFM UNIT ~ $\frac{3 \times 1330}{76.5} = 52.2$ LB/HR

AVG COOLING WATER RATE REQUIREMENT

1000 SCFM UNIT ~ 2675 GPH

10,000 SCFM UNIT ~ 26,750 GPH

20,000 SCFM UNIT ~ 53,500 GPH

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COMPUTATION SHEET

J. O. No. PS-228
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NAME OF COMPANY MSA RESEARCH CORP

SUBJECT ADSORPTION / INCINERATOR STUDY
(TRACE SOLVENT w/ CATALYST POISON)

THERMAL INCINERATOR

OUTLET TEMPERATURE TO BE 1450°F
MAKE-UP AIR @ 65°F AS REQUIRED
SOLVENT FEED STREAM @ 212°F
MIN. INCINERATOR SIZE TO BE ≈ 500 SCFM

BASIS:

				Cp
ADSORBER TO	93 LB ~	HEXANE ~ 46.5 LB	} = S	.75
INCINERATOR FEED -		BENZENE ~ 46.5 LB		.60
		STEAM ~ 279.0 LB		.50
		+		
		AIR ~ —		.26

ASSUME Cp OF INLET & OUTLET GASES ARE EQUAL APPROX. TO AIR @ .26 Btu/LB °F

$$\Delta H_R = \frac{(19{,}391 + 17{,}446)}{2}(.95) = 17{,}500 \text{ Btu/LB SOLVENT}$$

$$17{,}500\,(93) = .26\,W\,(1450 - T) \qquad (1)$$

$$W = S + A = 93 + 279 + A = 372 + A \quad (2)$$

WHERE S = LB SOLVENT STREAM
A = LB AIR

$$S\,C_{p_S}(212 - T) = A\,C_{p_A}(T - 65)$$

$$C_{p_S} = \frac{46.5\,(.75 + .60) + 279\,(.5)}{372}$$

$$372\,(.542)(212 - T) = .26A\,(T - 65)$$

$$42{,}700 - 202T = .26TA - 16.9A \quad (3)$$

$$C_{p_S} = \frac{62.9 + 139.5}{372} = \frac{202.4}{372} = .542$$

THE SOL'N IS TRIAL & ERROR

① ASSUME T = 90

THEN $W = \frac{17{,}500\,(93)}{.26\,(1360)} = 4600$

$$4600 = 372 + A$$

$$A = 4228 \text{ LB}$$

CHECKING IN EQUATION (3)

$$42{,}700 - 202T = .26A\,(T - 65)$$

SINGMASTER & BREYER

CHEMICAL & METALLURGICAL PROCESS ENGINEERS

COMPUTATION SHEET

J. O. No. PS-228

SHEET No. C-21 OF

DATE 9/2/71

COMP. BY STM C'K'D BY

NAME OF COMPANY MSA RESEARCH CORP

SUBJECT ADSORPTION/INCINERATION STUDY
(TRACE SOLVENT W/ CATALYST POISON)

$$42{,}700 - 202(90) = .26\,(4228)(25)$$
$$24{,}500 = 27{,}500$$

② ASSUME T = 85

THEN

$$W = \frac{17{,}500\,(93)}{.26\,(1365)} = 4575 \text{ LB}$$
$$A = 4575 - 372 = 4203 \text{ LB}$$

CHECKING . . .

$$42{,}700 - (202)85 = .26(4203)(20)$$
$$25{,}500 = 21{,}800$$

BASED ON ASSUMPTIONS 1 & 2 LET T = 87°F

$$W = \frac{17{,}500\,(93)}{.26\,(1363)} = 4580$$
$$A = 4580 - 372 = 4208$$

CHECK – .

$$C_{P_{AV}} \;\frac{.542(372) + 4208\,(.26)}{4580} = .28 \;\frac{\text{Btu}}{\text{LB}\,°\text{F}}$$

$$W = \frac{17{,}500(93)}{.28\,(1363)} = 4260 \text{ LB}$$
$$A = 3888$$

$$42{,}700 - 202(87) = .28\,(3888)(22)$$
$$25{,}200 \cong 24{,}000$$

SINGMASTER & BREYER
CHEMICAL & METALLURGICAL PROCESS ENGINEERS

COMPUTATION SHEET
J. O. No. PS-228
SHEET No. C-22 OF
DATE 9/2/71
COMP. BY STM C'K'D BY

NAME OF COMPANY MSA RESEARCH CORP
SUBJECT ADSORPTION/INCINERATION STUDY
(TRACE SOLVENT w/ CATALYST POISON)

VOLUME INCINERATOR FEED

$$\left(\frac{93}{82}+\frac{279}{18}\right)(359)\left(\frac{520}{492}\right) = 6320 \text{ SCF}$$

$$\left(\frac{3888}{29}\right)(359)\left(\frac{520}{492}\right) = 51\,000 \text{ SCF}$$

TOTAL 57,320 SCF

$$\frac{57,320}{93} = 619 \quad \frac{\text{SCF}}{\text{LB SOLVENT}}$$

ADSORBER - CAPACITY (SCFM)	INCINERATOR FEED SCF/CYCLE	*FEED TIME (MIN)	FEED RATE SCFM	INCINERATOR SIZE
1000	57,320	5520	10.4	500
10000	494,000	4750	104	500
20000	820,000	3960	207	500

* LOADING TIME x .86

NOTE: MIN. INCINERATOR SIZE TO BE 500 SCFM.

ADSORBER CAPACITY	ADSORB. CYCLES/YR	INCINERATOR OPERATION, (HR/CY)	INCINERATOR OPERATION HRS/YR
1000	55	1.91	105
10000	64	16.5	1060
20000	77	27.3	2110

CONSTRUCTION COST ESTIMATE

SINGMASTER & BREYER

CUSTOMER MSA Research Corp

LOCATION Evans City, Pa.

PROJECT PS-228

DESCRIPTION Hydrocarbon Emmisions Control via Adsorption & Solvent Recovery

Adsorption with Solvent Recovery (25% LEL)

PROP. NO.

CONT. NO.

MADE BY

APPROVED

ACCOUNT NUMBER	ITEM & DESCRIPTION	QUANTITY	UNIT	UNIT COSTS LABOR	UNIT COSTS SUB CONTR	UNIT COSTS MAT'L	ESTIMATED COST (CENTS OMITTED) LABOR	ESTIMATED COST SUB CONTRACTS	ESTIMATED COST MATERIALS	ESTIMATED COST TOTAL
	Dual Adsorber System: Capacity - 1000 SCFM Complete with two activated carbon adsorbers, adsorbing blower, blower, condenser, decanter, and instrumentation - Basis: Budget Quote. Blower HP - 15									35,000 —
	Precooler: Basis - Updated Correlation									5650 —
	Air Prefilter: Basis - Verbal Quote									650 —
	Land (Existing)									
	Excavation & Foundations Piping & Duct Work Installation of Adsorber System per Quote									10,000 —
	Insulation Electrical Painting Installation of Cooler & Filter @ 50% Cost									3150 —
									Sub Total	54,450 —
	Interest on Investment During Construction (One Month @ Prime Rate, @ 6%)									270 —
									Total Cap. Cost	54,720 —
									Say	54,700 —

CODE

(E 153)

DATE ______ REVISION NO. ______ REVISION DATE ______ PAGE NO. C-23

CONSTRUCTION COST ESTIMATE

SINGMASTER & BREYER

CUSTOMER MSA Research Corp

LOCATION Evans City, Pa.

PROJECT PS-228

DESCRIPTION Hydrocarbon Emmisions Control via Adsorption & Solvent Recovery

Adsorption with Solvent Recovery (25% LEL)

PROP. NO.

CONT. NO.

MADE BY

APPROVED

ACCOUNT NUMBER	ITEM & DESCRIPTION	QUANTITY	UNIT	UNIT COSTS LABOR	UNIT COSTS SUB CONTR	UNIT COSTS MAT'L	ESTIMATED COST (CENTS OMITTED) LABOR	ESTIMATED COST SUB CONTRACTS	ESTIMATED COST MATERIALS	ESTIMATED COST TOTAL
	Dual Adsorber System: Capacity - 10,000 SCFM. Complete with two activated carbon adsorbers, Adsorbing, Blower, Condenser, Decanter, & instrumenthtion: Basis: Budget Quote - 75HP Blower									70,000 —
	Precooler - Basis: Updated Correlation									22,250 —
	Air Prefilter - Verbal Quote.									675 —
	Land (Existing)									
	Excavation & Foundation } Installation of Adsorber System per Quote									15,000 —
	Piping & Duct Work									
	Insulation } Installation of Cooler & Filter @ 50% Cost									11,460 —
	Electrical									
	Painting								Sub-Total	119385 —
	Interest on Investment During Construction (1.5 Months @ Prime Rate @ 6%)									890 —
									Total Cap Cost	120,275 —
									Say	120,300 -

CODE

(E 153)

DATE ______ REVISION NO. ______ REVISION DATE ______ PAGE NO. C-24

CONSTRUCTION COST ESTIMATE

SINGMASTER & BREYER

CUSTOMER MSA Research Corp

LOCATION Evans City, Pa.

PROJECT PS-228

DESCRIPTION Hydrocarbon Emissions Control via Adsorption & Solvent Recovery

Adsorption with Solvent Recovery (25% LEL)

PROP. NO. ____

CONT. NO. ____

MADE BY ____

APPROVED ____

ACCOUNT NUMBER	ITEM & DESCRIPTION		QUANTITY	UNIT	UNIT COSTS			ESTIMATED COST CENTS OMITTED			
					LABOR	SUB CONTR	MAT'L	LABOR	SUB CONTRACTS	MATERIALS	TOTAL
	Dual Adsorber System: Capacity - 20,000 SCFM Complete with two activated carbon adsorbers, adsorbing, blower, condenser, decanter & instrumentation Basis: Budget Quote - 125HP Blower										110,000 —
	Precooler - Basis: Updated Correlation										42,750 —
	Air Prefilter: Verbal Quote.										725 —
	Land (Existing)										
	Excavation & Foundation	Installation of Absorber per Quote									30,000 —
	Piping & Duct Work										
	Insulation	Installation of Cooler & Filter @ 50% Cost									21,740 —
	Electrical										
	Painting									Sub-Total	205,215 —
	Interest on Investment During Construction (Two Months @ Prime Rate @ 6%)										2050 —
										Total Cap Cost	207,265 —
										Say	207,300 —

CODE

(E 153)

DATE ____ REVISION NO. ____ REVISION DATE ____ PAGE NO. C-25

CONSTRUCTION COST ESTIMATE

SINGMASTER & BREYER

CUSTOMER MSA Research Corp

LOCATION Evans City, Pa.

PROJECT PS-228

DESCRIPTION Hydrocarbon Emmision Control
Adsorption with Incineration ~ No
Heat Recovery
(25% LEL)

PROP. NO.
CONT. NO.
MADE BY
APPROVED

ACCOUNT NUMBER	ITEM & DESCRIPTION	QUANTITY	UNIT	UNIT COSTS LABOR	UNIT COSTS SUB CONTR	UNIT COSTS MAT'L	ESTIMATED COST (CENTS OMITTED) LABOR	ESTIMATED COST SUB CONTRACTS	ESTIMATED COST MATERIALS	ESTIMATED COST TOTAL
	Dual Adsorber - Capacity 1000 SCFM. with 15 HP Blower; Basis: Budget Quote ~ . Cost of Condenser & Decanter obtained by updated correlation & deleted from quote									33,600 —
	Precooler - Basis: Updated Correlation									5,650 —
	Air Prefilter - Verbal Quote									650 —
	Thermal Incinerator & 3 HP Booster Fan Basis: Correlation from Quotes									8500 —
	Land (Existing)									
	Excavation & Foundations Piping, Ductwork, & Insulation } Adsorber Install. per Quote									10,000 —
	Electrical Painting } Incinerator, Cooler, Filter, Install @ 50% Cost									7,400 —
									Sub-Total	65,800 —
	Interest on Investment During Constr (Three Months @ Prime Rate @ 6%)									1,000 —
									Total Cap Cost	66,800
CODE										

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DATE ______ REVISION NO. ______ REVISION DATE ______ PAGE NO. C-26

CONSTRUCTION COST ESTIMATE

SINGMASTER & BREYER

CUSTOMER MSA Research Corp.

LOCATION Evans City, Pa

PROJECT PS-228

DESCRIPTION Hydrocarbon Emmision Control
Adsorption with Incineration ~ No Heat Recovery
(25% LEL)

PROP. NO.
CONT. NO.
MADE BY
APPROVED

ACCOUNT NUMBER	ITEM & DESCRIPTION	QUANTITY	UNIT	UNIT COSTS			ESTIMATED COST CENTS OMITTED			
				LABOR	SUB CONTR	MAT'L	LABOR	SUB CONTRACTS	MATERIALS	TOTAL
	Dual Adsorber - Capacity 10,000 SCFM - with 75 HP Blower; Basis: Budget Quote - Cost of Condenser & Decanter Obtained by UpDated Correlation & Deducted from Quote									66,100 —
	Precooler - Basis: Updated Corration									22,250 —
	Air Prefilter - Verbal Quote									675 —
	Thermal Incinerator & 25 HP Booster Fan Basis: Correlation Developed from Quotes									22,000 —
	Land (Existing)									
	Excavation & Foundations Piping, Ductwork, & Insulation } Adsorber Installation per Quote									15,000 —
	Electrical Painting } Incinerator, Cooler, Filter Install @ 50% Cost									22,460 —
									Sub-Total	148,485 —
	Interest on Investment During Const. (Three Months @ Prime Rate @ 6%)									2,250 —
									Total Cap Cost	150,735 —
CODE									Say	150,700 —

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DATE ______ REVISION NO. ______ REVISION DATE ______ PAGE NO. C-27

CONSTRUCTION COST ESTIMATE

SINGMASTER & BREYER

CUSTOMER MSA Research Corp.

LOCATION Evans City, Pa

PROJECT PS-228

DESCRIPTION Hydrocarbon Emmisions Control
Adsorption with Incineration ~ No Heat Recovery
(25% LEL)

PROP. NO.
CONT. NO.
MADE BY
APPROVED

ACCOUNT NUMBER	ITEM & DESCRIPTION	QUANTITY	UNIT	UNIT COSTS			ESTIMATED COST CENTS OMITTED			
				LABOR	SUB CONTR	MAT'L	LABOR	SUB CONTRACTS	MATERIALS	TOTAL
	Dual Adsorber - Capacity: 20,000 SCFM - with 125 HP Blower; Basis: Budget Quote ~ Cost of Condenser & Decanter Obtained by UpDated Correlation & Deducted from Quote									104,340 —
	Precooler - Basis: UpDated Correlation									42,750 —
	Air Prefilter - Verbal Quote									725 —
	Thermal Incinerator & 50 HP Booster Fan Basis: Correlation Developed From Quotes									35,500 —
	Land (Existing)									
	Excavation & Foundations } Installation Adsorber per Quote									30,000 —
	Piping, Ductwork, & Insulation									
	Electrical } Incinerator, Cooler, Filter Install @ 60% Cost									39,500 —
	Painting									
									Sub-Total	252815 —
	Interest on Investment During Constr. (Three Months @ Prime Rate @ 6%)									3,800 —
									Tot. Capital Cost	256,615 —
									Say	256,600 —

CODE

(E 153)

DATE ______ REVISION NO. ______ REVISION DATE ______ PAGE NO. C-28.

CONSTRUCTION COST ESTIMATE

SINGMASTER & BREYER

CUSTOMER MSA Research Corporation

LOCATION Evans City, Pa.

PROJECT PS-228

DESCRIPTION Hydrocarbon Emmisions Control via Adsorption with Thermal Incineration & Heat Recovery (Primary) - (25% LEL)

Adsorption with Incineration

PROP. NO.

CONT. NO.

MADE BY

APPROVED

ACCOUNT NUMBER	ITEM & DESCRIPTION	QUANTITY	UNIT	UNIT COSTS LABOR	UNIT COSTS SUB CONTR	UNIT COSTS MAT'L	ESTIMATED COST (CENTS OMITTED) LABOR	ESTIMATED COST SUB CONTRACTS	ESTIMATED COST MATERIALS	ESTIMATED COST TOTAL
	Dual Adsorber System Capacity - 1000 SCFM, Complete with two activated carbon adsorbers & Adsorption Blower; ~ Basis ~ Budget quote less estimated amount for condenser and decanter obtained by use of updated correlation 15HP Blower									33,600 —
	Precooler - Basis: Updated Correlation									5650 —
	Air Prefilter - Verbal Quote									650 —
	Thermal Incinerator with Heat Recovery Unit; Basis: Correlation developed from UOP budget quotes - 5HP Blower									14,400 —
	Land (Existing)									
	Excavation & Foundation Piping & Duct Work } Installation Adsorber System per Quote									10,000 —
	Insulation Electrical Painting } Installation Incinerator, Cooler, & Filter @ 50% Cost									10,350 —
									Sub-Total	74,650
	Interest on Investment During Constr. (Three Months @ Prime Rate @ 6%)									1,120
									Total	75,770
									Say	75,800 —

CODE

(E 153)

DATE ______ REVISION NO. ______ REVISION DATE ______ PAGE NO. C-29.

CONSTRUCTION COST ESTIMATE

SINGMASTER & BREYER

CUSTOMER MSA Research Corporation

LOCATION Evans City, Pa

PROJECT PS-228

DESCRIPTION Hydrocarbon Emmisions Control via Adsorption with Thermal Incineration & Heat Recovery (Primary) - (25% LEL)

Adsorption with Incineration

PROP. NO.

CONT. NO.

MADE BY

APPROVED

ACCOUNT NUMBER	ITEM & DESCRIPTION		QUANTITY	UNIT	UNIT COSTS			ESTIMATED COST CENTS OMITTED			
					LABOR	SUB CONTR	MAT'L	LABOR	SUB CONTRACTS	MATERIALS	TOTAL
	Dual Adsorber System Capacity 10,000 SCFM, Complete with two activated carbon adsorbers & Adsorbtion Blower; Basis: budget quote less estimated amount for condenser and decanter obtained by use of updated correlation - 75HP Blower										66,100 —
	Precooler - Basis: Updated Correlation										22,250 —
	Air Prefilter - Verbal Quote -										675 —
	Thermal Incinerator with Heat Recovery Unit; Basis: Correlation developed from budget quotes - 50 HP Blower										48,000 —
	Land (Existing)										
	Excavation & Foundation Piping & Duct Work Insulation	Installation - Adsorption System per Quote									15,000 —
	Electrical Painting	Installation Incinerator, Cooler, & Filter @ 50%									35,500 —
										Sub-Total	187,525
	Interest on Investment During Constr. (Three Months @ Prime Rate @ 6%)										.2800
										Total Cap Cost	190,325 —
										Say	190,300 —

CODE

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DATE ______ REVISION NO. ______ REVISION DATE ______ PAGE NO. C-30

CONSTRUCTION COST ESTIMATE

SINGMASTER & BREYER

CUSTOMER MSA Research Corporation
LOCATION Evans City, Pa
PROJECT PS-228

DESCRIPTION Hydrocarbon Emmisions Control via Adsorption with Thermal Incineration & Heat Recovery (Primary) - (25% LEL)

Adsorption with Incineration

PROP. NO.
CONT. NO.
MADE BY
APPROVED

ACCOUNT NUMBER	ITEM & DESCRIPTION	QUANTITY	UNIT	UNIT COSTS			ESTIMATED COST CENTS OMITTED			
				LABOR	SUB CONTR	MAT'L	LABOR	SUB CONTRACTS	MATERIALS	TOTAL
	Dual Adsorber System Capacity 20,000 SCFM, Complete with two activated carbon adsorbers & Adsorption Blower; ~ Basis: Budget quote less estimated amount for condenser and decanter obtained by use of updated correlation - 125 HP Blower									104,340
	Precooler - Basis: Updated Correlation									42,750 —
	Air Prefilter - Verbal Quote.									725 —
	Thermal Incinerator with Heat Recovery Unit; Basis: Correlation developed from budget ~100 HP Blower									78,000 —
	Land (Existing)									
	Excavation & Foundation } Installation Adsorber System - Per Quote									30,000 —
	Piping & Duct Work									
	Insulation } Installation Incinerator, Cooler & Filter @ 50% Cost									60,750 —
	Electrical									
	Painting									
									Sub-Total	316,565 —
	Interest on Investment During Construction (Three Months @ Prime Rate @ 6%)									4,750 —
CODE									Total Cap. Cost	321,315 —
									Say	321,300 —

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DATE ______ REVISION NO. ______ REVISION DATE ______ PAGE NO. C-31

CONSTRUCTION COST ESTIMATE

SINGMASTER & BREYER

CUSTOMER MSA Research Corp.

LOCATION Evans City, Pa.

PROJECT PS-228

DESCRIPTION Hydrocarbon Emmisions Control via Adsorption with Thermal Incineration & Heat Recovery

Adsorption with Incineration, Primary, & Secondary Heat Recovery (25 % LEL)

PROP. NO.

CONT. NO.

MADE BY

APPROVED

ACCOUNT NUMBER	ITEM & DESCRIPTION	QUANTITY	UNIT	UNIT COSTS			ESTIMATED COST CENTS OMITTED			
				LABOR	SUB CONTR	MAT'L	LABOR	SUB CONTRACTS	MATERIALS	TOTAL
	Dual Adsorber, 15 HP Blower- Capacity: 1000 SCFM Basis: Budget Quote Cost of Condenser & Decanter obtained by up-dated Correlation & Deducted from Quote									33,600 —
	Precooler - Basis: Updated Correlation									5,650 —
	Air Prefilter - Verbal Quote.									650 —
	Thermal Incinerator & Primary Heat Exchanger Booster Fan - 5 HP; Basis: Correlation developed from Budget Quotes.									14,400 —
	Secondary Heat Exchanger & 5 HP Blower Basis: Correlation from Quotes.									6,400 —
	Land (Existing)									
	Excavation & Foundations									10,000 —
	Piping, Ductwork, & Insulation									10,350 —
	Electrical									
	Painting									6,400 —
	Adsorber Install. per Quote Incinerator/Prim. Ht. Exchr., Cooler, Filter @ 50% Cost Sec. Ht. Exch @ 100% Cost									
									Sub-Total	87,450 —
	Interest on Investment During Const. (Three Months @ Prime Rate @ 6%)									1,300 —
CODE									Total Capital Cost	88,750
									Say	88,800 —

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DATE ______ REVISION NO. ______ REVISION DATE ______ PAGE NO. C-32

CONSTRUCTION COST ESTIMATE

SINGMASTER & BREYER

CUSTOMER MSA Research Corp.

LOCATION Evans City, Pa

PROJECT PS-228

DESCRIPTION Hydrocarbon Emmisions Control via Adsorption with Thermal Incineration & Heat Recovery
Adsorption with Incineration, Primary, & Secondary Heat Recovery (25% LEL)

PROP. NO.

CONT. NO.

MADE BY l

APPROVED

ACCOUNT NUMBER	ITEM & DESCRIPTION	QUANTITY	UNIT	UNIT COSTS			ESTIMATED COST CENTS OMITTED			
				LABOR	SUB CONTR	MAT'L	LABOR	SUB CONTRACTS	MATERIALS	TOTAL
	Dual Adsorber, 75HP Blower- Capacity: 10,000 SCFM Basis: Budget Quote Cost of Condenser & Decanter Obtained by Up-Dated Correlation & Deducted from Quote									66,100 —
	Precooler - Basis: Updated Correlation									22,250 —
	Air Prefilter - Verbal Quote -									675 —
	Thermal Incinerator & Primary Heat Exchanger Booster Fan - 50HP; Basis: Correlation Developed from Budget Quote									48,000 —
	Secondary Heat Exchanger & 50HP Blower Basis: Correlation from Budget Quote									24,500 —
	Land (Existing)									
	Excavation & Foundations									15,000 —
	Piping, Ductwork, & Insulation									35,500 —
	Electrical									
	Painting									24,500 —
	Adsorber Install per Quote Incinerator/Pri. Ht. Exchr, Cooler & Filter Installation @ 60% Cost. Install Sec. Ht. Exchr. @ 100% Cost								Sub Total	236,525 —
	Interest on Investment During Const. (Three Months @ Prime Rate @ 6%)									3,550 —
									Total Cap Cost	239,875 —
									Say	239,900 —

CODE

(E 153)

DATE ______ REVISION NO. ______ REVISION DATE ______ PAGE NO. C-33

CONSTRUCTION COST ESTIMATE

SINGMASTER & BREYER

CUSTOMER MSA Research Corp.

LOCATION Evans City, Pa

PROJECT PS- 228

DESCRIPTION Hydrocarbon Emmisions Control via Adsorption with Thermal Incineration & Heat Recovery

Adsorption with Incineration, Primary, & Secondary Heat Recovery (25% LEL)

PROP. NO. ____

CONT. NO. ____

MADE BY ____

APPROVED ____

ACCOUNT NUMBER	ITEM & DESCRIPTION	QUANTITY	UNIT	UNIT COSTS LABOR	UNIT COSTS SUB CONTR	UNIT COSTS MAT'L	ESTIMATED COST (CENTS OMITTED) LABOR	ESTIMATED COST (CENTS OMITTED) SUB CONTRACTS	ESTIMATED COST (CENTS OMITTED) MATERIALS	ESTIMATED COST (CENTS OMITTED) TOTAL
	Dual Adsorber System, 125HP Blower- Capacity: 20,000 SCFM Basis: Budget Quote Cost of Condenser & Decanter Obtained by Updated Correlation & Deducted from Quote									104,340 —
	Precooler - Basis: Updated Correlation									42,750 —
	Air Prefilter									725 —
	Thermal Incinerator & Primary Heat Exchanger Booster Fan-100HP; Basis: Correlation Developed from Budget Quote									78,000 —
	Secondary Heat Exchanger & 100 HP Blower Basis: Correlation from Quote									38,000 —
	Land (Existing)									
	Excavation & Foundations Installation of Adsorber per Quote									30,000 —
	Piping, Ductwork, & Insulation Install Incinerator, Pri Ht Exchr, Filter, Cooler @ 50% Cost									60,750 —
	Electrical									
	Painting Install Sec Ht Exchr @100% Cost									38,000 —
									Sub-Total	392,565 —
	Interest on Investment During Constr. (Three Months @ Prime Rate @ 6%)									5,900 —
									Total Cap Cost	398,465
									Say	398,500

CODE

(E 153)

DATE ____ REVISION NO. ____ REVISION DATE ____ PAGE NO. C-3A

CONSTRUCTION COST ESTIMATE

SINGMASTER & BREYER

CUSTOMER MSA Research Corp
LOCATION Evans City, Pa
PROJECT PS-228

DESCRIPTION Hydrocarbon Emmisions Control
Adsorption and Thermal Incineration
(Trace Solv. Conc. with Catalyst Poison)

PROP. NO.
CONT. NO.
MADE BY
APPROVED

ACCOUNT NUMBER	ITEM & DESCRIPTION	QUANTITY	UNIT	UNIT COSTS			ESTIMATED COST CENTS OMITTED			
				LABOR	SUB CONTR	MAT'L	LABOR	SUB CONTRACTS	MATERIALS	TOTAL
	Dual Adsorber System: Capacity: 1000 SCFM with 15HP Blower Basis: Budget Quote ~ : Cost of Condenser & Decanter Deducted Based on Price Correlation									33,600 –
	Precooler - Basis: Updated Correlation									5,650 –
	Air Prefilter-Verbal Quote-									650 –
	Thermal Incinerator & 3 HP Booster Fans Basis: Correlation Developed from Budget Quotes									8500 –
	Land (Existing)									
	Excavations & Foundations } Adsorber Installation									10,000 –
	Piping, Duct Work, Insulation } Cost per Quote									
	Electrical } Incinerator, Cooler, Filter									7,400 –
	Painting } Install. Cost @ 50%									
									Sub-Total	65,800 –
	Interest on Investment During Constr. (Three Months @ Prime Rate @ 6%)									990 –
CODE									Total Cap Cost	66,790 –
									Say	66,800 –

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DATE ________ REVISION NO. ________ REVISION DATE ________ PAGE NO. C-35

CONSTRUCTION COST ESTIMATE

SINGMASTER & BREYER

CUSTOMER MSA Research Corp
LOCATION Evans City, Pa
PROJECT PS-228

DESCRIPTION Hydrocarbon Emmisions Control
Adsorption and Thermal Incineration
(Trace Solvent Conc. with Catalyst Poison)

PROP. NO.
CONT. NO.
MADE BY
APPROVED

ACCOUNT NUMBER	ITEM & DESCRIPTION	QUANTITY	UNIT	UNIT COSTS			ESTIMATED COST CENTS OMITTED			
				LABOR	SUB CONTR	MAT'L	LABOR	SUB CONTRACTS	MATERIALS	TOTAL
	Dual Adsorber System: Capacity- 10,000 SCFM with 75 HP Blower, Basis: Budget Quote with Cost of Condenser & Decanter Deducted based on price correlation									66,100 –
	Precooler - Basis Updated Correlation									22,250 –
	Air Prefilter - Verbal Quote.									675 –
	Thermal Incinerator with 3 HP Booster Fan, Basis: Correlation Developed from Budget Quotes									8500 –
	Land (Existing)									
	Excavation & Foundations } Adsorper Installation Cost per Quote									15,000 –
	Piping, Ductwork, Insulation }									
	Electrical } Incinerator, Cooler, Filter, Install. Cost @ 50%									15,700 –
	Painting }									
									Sub Total	128,225 –
	Interest on Investment During Constr. (Three Months @ Prime Rate @ 6%)									1,925 –
									Total Cap Cost	130,150 –
CODE									Say	130,200 –

(E 153)

DATE ______ REVISION NO. ______ REVISION DATE ______

CONSTRUCTION COST ESTIMATE

SINGMASTER & BREYER

CUSTOMER MSA Research Corp

LOCATION Evans City, Pa

PROJECT PS-228

DESCRIPTION Hydrocarbon Emmisions Control Adsorption and Thermal Incineration (Trace Solvent Conc. with Catalyst Poison)

PROP. NO.

CONT. NO.

MADE BY

APPROVED

ACCOUNT NUMBER	ITEM & DESCRIPTION	QUANTITY	UNIT	UNIT COSTS			ESTIMATED COST CENTS OMITTED			
				LABOR	SUB CONTR	MAT'L	LABOR	SUB CONTRACTS	MATERIALS	TOTAL
	Dual Adsorber System: Capacity - 20,000 SCFM with 125HP Blower Basis: Budget, Quote with Cost of Condensor & Decanter Deducted based on price correlation									104,340 —
	Precooler - Basis: Updated Correlation									42,750 —
	Air Prefilter - Verbal Quote									725 —
	Thermal Incinerator with 3 HP Booster Fan, Basis: Correlation Developed from Budget Quotes									8500 —
	Land (Existing)									
	Excavation & Foundations } Install. Cost of Adsorber per Quote									30,000 —
	Piping, Ductwork, Insulation }									
	Electrical } Incinerator, Cooler, Filter, Installed @ 50% Cost.									52,000 —
	Painting }								Sub Total	238,315 —
	Interest on Investment During Construction (Three Months @ Prime Rate @ 6%)									3575 —
									Total Cap Cost	241,890 —
									Say	241,900 —

CODE

(E 153)

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MANUFACTURING ESTIMATE - OVEN EXHAUST CONTROL SCHEME

CONTROL PROCESS: ADSORPTION WITH SOLVENT RECOVERY ~ OVEN EXHAUST RATE: 1000 SCFM

PROCESS OPERATING TIME: 2 SHIFTS/DAY 365 DAYS/YR 5840 HR/YR (25% LEL)

ITEM	DESCRIPTION	COST $/YR	 $/M SCF
RAW MATERIALS			
UTILITIES:			
COOLING WATER	$.03/10³ GAL. × 3560 GPH × 5840 HR/YR = $623	623	
STEAM	$1.00/10³ LB × 111 LB/HR × 5840 HR/YR =	647	
NATURAL GAS	$.60/10⁶ Btu –	—	
ELECTRICITY	$.015/KWH × 15 HP × .746 KW/HP × 5840 HR/YR =	980	
MAINTENANCE:			
GENERAL MAINT.	5% CAPITAL COST (54,450)	2722	
MAINT. SUPPLIES	5600 LB × 1/5 YR × $50/LB	560	
DIRECT LABOR:	.5 HR/SHIFT × 730 SHIFTS/YR × $4.00/HR	1460	
SUPERVISION:	10% DIRECT LABOR	146	
DIRECT MFG. COST		7138	
PAYROLL OVERHEAD:	30% DIRECT LABOR	438	
PLANT OVERHEAD:	50% DIRECT LABOR	730	
PACKAGING:		—	
SHIPPING:		—	
INDIRECT MFG. COST		1168	
DEPRECIATION:	10% CAPITAL COST (54,720)	5472	
PROPERTY TAXES:	1% CAPITAL COST (54,720)	547	
INSURANCE:	0.5% CAPITAL COST (54,450)	272	
FIXED MFG COST		6291	
TOTAL PLANT LEVEL COST		14,597	
CORPORATE OVERHEAD	3% TOTAL PLANT LEVEL COST	438	
TOTAL-MFG COST		15,035	
	SAVINGS FOR RECOVERED SOLVENT: LESS	5,580	
	$10.7 \frac{LB}{HR} \times \$\frac{.03}{LB} \times 5840 \frac{HR}{YR} = \$1880$ COST	$9,455	.027
	$16.9 \times .0375 \times 5840 = \$3700$ SAY	$9,500	
	5580		

MANUFACTURING ESTIMATE - OVEN EXHAUST CONTROL SCHEME

CONTROL PROCESS: ABSORPTION WITH SOLVENT RECOVERY ~ OVEN EXHAUST RATE: 10,000 SCFM

PROCESS OPERATING TIME: 2 SHIFTS/DAY 365 DAYS/YR 5840 HR/YR (25% LEL)

ITEM	DESCRIPTION	COST	
		$/YR	$/M SCF
RAW MATERIALS			
UTILITIES:			
COOLING WATER	$.03/10³ GAL. × 35,600 GPH × 5840 HR/YR	6230	
STEAM	$ 1.00/10³ LB × 1110 LB/HR × 5840 HR/YR	6470	
NATURAL GAS	$ .60/10⁶ Btu		
ELECTRICITY	$ .015/KWH × 75 HP × .746 KW/HP × 5840 HR/YR	4900	
MAINTENANCE:			
GENERAL MAINT.	5% CAPITAL COST (119,385)	5969	
MAINT. SUPPLIES	48,000 LB × 1/5 YR $.50/LB	4800	
DIRECT LABOR:	.5 HR/SHIFT × 730 SHIFTS/YR × $ 4.00/HR	1460	
SUPERVISION:	10% DIRECT LABOR	146	
DIRECT MFG. COST		29,975	
PAYROLL OVERHEAD	30% DIRECT LABOR	438	
PLANT OVERHEAD:	50% DIRECT LABOR	730	
PACKAGING:		–	
SHIPPING:		–	
INDIRECT MFG. COST		1168	
DEPRECIATION:	10% CAPITAL COST (120,275)	12,027	
PROPERTY TAXES:	1% CAPITAL COST (120,275)	1203	
INSURANCE:	0.5% CAPITAL COST (119,385)	597	
FIXED MFG COST		13827	
TOTAL PLANT LEVEL COST		44,970	
CORPORATE OVERHEAD	3% TOTAL PLANT LEVEL COST	1349	
TOTAL MFG COST		46,319	
	SAVINGS FOR RECOVERED SOLVENT: LESS	55,800	
	$107 \frac{LB}{HR} \times \frac{\$.03}{LB} \times 5840 \frac{HR}{YR} = \$18,800$ SAVINGS	9,481	
	$169 \frac{LB}{HR} \times \$.0375/LB \times 5840 \frac{HR}{YR} = 37,000$ SAY	$9,500	.0027
	$55,800		

MANUFACTURING ESTIMATE - OVEN EXHAUST CONTROL SCHEME

CONTROL PROCESS: ADSORPTION WITH SOLVENT RECOVERY ~ OVEN EXHAUST RATE: 20,000

PROCESS OPERATING TIME: 2 $\frac{SHIFTS}{DAY}$ 365 $\frac{DAYS}{YR}$ 5840 $\frac{HR}{YR}$ (25% LEL)

ITEM	DESCRIPTION	COST $/YR	 $/M SCF
RAW MATERIALS			
UTILITIES:			
COOLING WATER	$.03/10³ GAL. × 11,200 GPM × 5840 HR/YR = $12,500	12,500	
STEAM	$1.00/10³ LB × 2220 LB/HR × 5840 HR/YR = $13,000	13,000	
NATURAL GAS	$.60/10⁶ Btu		
ELECTRICITY	$.015/KWH × 125 HP × .746 KW/HP × 5840 HR/YR = $8,180	8,180	
MAINTENANCE:		10,260	
GENERAL MAINT.	5% CAPITAL COST $(205,215)		
MAINT. SUPPLIES	80,000 LB × 1/5 YR × $.5/LB = $8000	8000	
DIRECT LABOR:	.5 HR/SHIFT × 730 SHIFTS/YR × $4.00/HR =	1460	
SUPERVISION:	10% DIRECT LABOR	146	
DIRECT MFG. COST		53546	
PAYROLL OVERHEAD:	30% DIRECT LABOR	438	
PLANT OVERHEAD:	50% DIRECT LABOR	730	
PACKAGING:		-	
SHIPPING:		-	
INDIRECT MFG. COST		1168	
DEPRECIATION:	10% CAPITAL COST (207,265)	20,726	
PROPERTY TAXES:	1% CAPITAL COST (207,265)	2,073	
INSURANCE:	0.5% CAPITAL COST (205,215)	1,026	
FIXED MFG COST		23,825	
TOTAL PLANT LEVEL COST		78,539	
CORPORATE OVERHEAD	3% TOTAL PLANT LEVEL COST	2,356	
TOTAL MFG COST		80,895	
	SAVINGS FOR RECOVERED SOLVENT — LESS	111,600	
	SAVINGS	30,705	
	SAY	30,700	.0044
	$214 \frac{LB}{HR} \times \frac{\$.03}{LB} \times 5840 \frac{HR}{YR} = \$37,600$		
	$338 \frac{LB}{HR} \times \frac{\$.0375}{LB} \times 5840 \frac{HR}{YR} = 74,000$		
	111,600		

MANUFACTURING ESTIMATE - OVEN EXHAUST CONTROL SCHEME

CONTROL PROCESS: ADSORPTION WITH INCINERATION AND NO HEAT RECOVERY ~ OVEN EXHAUST RATE ~ 1000 SCFM (25% LEL)

PROCESS OPERATING TIME: 2 SHIFTS/DAY 365 DAYS/YR 5840 HR/YR

ITEM	DESCRIPTION	COST $/YR	COST $/MSCF
RAW MATERIALS			
UTILITIES:			
COOLING WATER	$.03/10³ GAL × 2675 GAL/HR × 5840 HR/YR	470	
STEAM	$1.00/10³ LB × 111 LB/HR × 5840 HR/YR	647	
NATURAL GAS	$.60/10⁶ BTU —	1180	
ELECTRICITY	$.015/KWH × 18 HP × .746 KW/HP × 5840 HR/YR		
MAINTENANCE:		3290	
GENERAL MAINT.	5% CAPITAL COST (65,800)		
MAINT. SUPPLIES	5600 LB × 1/5 YR × $.50/LB	560	
DIRECT LABOR:	.5 HR/SHIFT × 730 SHIFT/YR × $4/HR	1460	
SUPERVISION:	10% DIRECT LABOR	146	
DIRECT MFG. COST		7753	
PAYROLL OVERHEAD:	30% DIRECT LABOR	438	
PLANT OVERHEAD:	50% DIRECT LABOR	730	
PACKAGING:			
SHIPPING:			
INDIRECT MFG. COST		1168	
DEPRECIATION:	10% CAPITAL COST (66,800)	6680	
PROPERTY TAXES:	1% CAPITAL COST (66,800)	668	
INSURANCE:	0.5% CAPITAL COST (65,800)	329	
FIXED MFG COST		7677	
TOTAL PLANT LEVEL COST		16,598	
CORPORATE OVERHEAD	3% TOTAL PLANT LEVEL COST	498	
TOTAL MFG COST		17,096	
	SAY	17,100	.049

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MANUFACTURING ESTIMATE - OVEN EXHAUST CONTROL SCHEME

CONTROL PROCESS: ADSORPTION WITH INCINERATION AND NO HEAT RECOVERY ~ OVEN EXHAUST.

PROCESS OPERATING TIME: 2 SHIFTS/DAY 365 DAYS/YR 5840 HR/YR

RATE - 10,000 SCFM (25% LEL)

ITEM	DESCRIPTION	COST $/YR	COST $/M SCF
RAW MATERIALS			
UTILITIES:			
COOLING WATER	$.03/$10^3$ GAL. × 26,750 GAL/HR × 5840 HR/YR	4700	
STEAM	$1.00/$10^3$ LB × 1110 LB/HR × 5840 HR/YR	6470	
NATURAL GAS	$.60/$10^6$ Btu		
ELECTRICITY	$.015/KWH × .746 KW/HP × 100 HP × 5840 HR/YR	6550	
MAINTENANCE:			
GENERAL MAINT.	5% CAPITAL COST (148,485)	7424	
MAINT. SUPPLIES	48,000 LB × 1/5 YR × $.50/LB	4800	
DIRECT LABOR:	.5 HR/SHIFT × 730 SHIFT/YR × $4/HR	1460	
SUPERVISION:	10% DIRECT LABOR	146	
DIRECT MFG. COST		31550	
PAYROLL OVERHEAD	30% DIRECT LABOR	438	
PLANT OVERHEAD:	50% DIRECT LABOR	730	
PACKAGING:		–	
SHIPPING:		–	
INDIRECT MFG. COST		1168	
DEPRECIATION:	10% CAPITAL COST (150,735)	15074	
PROPERTY TAXES:	1% CAPITAL COST (150,735)	1507	
INSURANCE:	0.5% CAPITAL COST (148,485)	742	
FIXED MFG COST		17323	
TOTAL PLANT LEVEL COST		50,041	
CORPORATE OVERHEAD	3% TOTAL PLANT LEVEL COST	1501	
TOTAL - MFG COST		51,542	
	SAY	51,500	.0147

MANUFACTURING ESTIMATE - OVEN EXHAUST CONTROL SCHEME

CONTROL PROCESS: ADSORPTION WITH INCINERATION & NO HEAT RECOVERY ~ OVEN EXHAUST RATE ≈ 20,000 SCFM (25% LEL)

PROCESS OPERATING TIME: 2 SHIFTS/DAY 365 DAYS/YR 5840 HR/YR

ITEM	DESCRIPTION	COST $/YR	 $/MSCF
RAW MATERIALS			
UTILITIES:			
COOLING WATER	$.03/10³ GAL. × 53,500 GAL/HR × 5840 HR/YR	9,400	
STEAM	$1.00/10³ LB × 2220 LB/HR × 5840 HR/YR	12,940	
NATURAL GAS	$.60/10⁶ Btu		
ELECTRICITY	$.015/KWH × 175 HP × .746 KW/HP × 5840 HR/YR	11,500	
MAINTENANCE:			
GENERAL MAINT.	5% CAPITAL COST (252,815)	12640	
MAINT. SUPPLIES	80,000 LB × 1/5 YR × $.50/LB	8000	
DIRECT LABOR:	.5 HR/SHIFT × 730 SHIFTS/YR × $4/HR	1460	
SUPERVISION:	10% DIRECT LABOR	146	
DIRECT MFG. COST		56,086	
PAYROLL OVERHEAD	30% DIRECT LABOR	438	
PLANT OVERHEAD:	50% DIRECT LABOR	730	
PACKAGING:		–	
SHIPPING:		–	
INDIRECT MFG. COST		1138	
DEPRECIATION:	10% CAPITAL COST (256,615)	25,662	
PROPERTY TAXES:	1% CAPITAL COST (256,615)	2566	
INSURANCE:	0.5% CAPITAL COST (252,815)	1264	
FIXED MFG COST		29492	
TOTAL PLANT LEVEL COST		86,716	
CORPORATE OVERHEAD	3% TOTAL PLANT LEVEL COST	2601	
TOTAL - MFG COST		89,317	
	SAY	89,300	.0128

MANUFACTURING ESTIMATE - OVEN EXHAUST CONTROL SCHEME

CONTROL PROCESS: ABSORPTION WITH *INCINERATION & PRIMARY HT. RECOVERY ~ OVEN EXHAUST: 1000 SCFM (25% LEL)

PROCESS OPERATING TIME: 2 SHIFTS/DAY 365 DAYS/YR 5840 HR/YR

		COST	
ITEM	DESCRIPTION	$/YR	$/M SCF
RAW MATERIALS			
UTILITIES:			
COOLING WATER	$ .03/10^3 GAL. × 2675 GPH × 5840 HR/YR	470	
STEAM	$ 1.00/10^3 LB × 111 $\frac{LB}{HR}$ × 5840 HR/YR =	647	
NATURAL GAS	$ .60/10^6 Btu —	—	
ELECTRICITY	$ .015/KWH × .746 $\frac{KW}{HP}$ × 5840 $\frac{HR}{YR}$ × (15 + .86(5)) HP = $ 1260	1260	
MAINTENANCE:		3 732	
GENERAL MAINT.	5% CAPITAL COST (74650)		
MAINT. SUPPLIES	5600 LB × 1/5 YR × $ .50/LB	560	
DIRECT LABOR:	.5 HR/SHIFT × 730 SHIFT/YR × $4.00/HR	1460	
SUPERVISION:	10% DIRECT LABOR	146	
DIRECT MFG. COST		8275	
PAYROLL OVERHEAD	30% DIRECT LABOR	438	
PLANT OVERHEAD:	50% DIRECT LABOR	730	
PACKAGING:		—	
SHIPPING:		—	
INDIRECT MFG. COST		1168	
DEPRECIATION:	10% CAPITAL COST (75,770)	7577	
PROPERTY TAXES:	1% CAPITAL COST (75,770)	758	
INSURANCE:	0.5% CAPITAL COST (74,650)	373	
FIXED MFG COST		8708	
TOTAL PLANT LEVEL COST		18,151	
CORPORATE OVERHEAD	3% TOTAL PLANT LEVEL COST	545	
TOTAL-MFG COST		18696	
	SAY	$18,700	.054

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* CASE EVALUATED IS THERMAL INCINERATION

MANUFACTURING ESTIMATE - OVEN EXHAUST CONTROL SCHEME

CONTROL PROCESS: ABSORPTION WITH INCINERATION & PRI. HT. RECOVERY ~ OVEN EXHAUST: 10,000 SCFM

PROCESS OPERATING TIME: 2 SHIFTS/DAY 365 DAYS/YR 5840 HR/YR (25% LEL)

ITEM	DESCRIPTION	COST	
		$/YR	$/MSCF
RAW MATERIALS			
UTILITIES:			
COOLING WATER	$.03/$10^3$ GAL. × 26,750 GPH × 5840 HR/YR	4700	
STEAM	$ 1.00/10^3 LB × 110 LB/HR × 5840 HR/YR	6470	
NATURAL GAS	$ .60/10^6 BTU		
ELECTRICITY	$ .015/KWH × .746 KW/HP × 5840 HR/YR × (75 + .86(50))HP	7700	
MAINTENANCE:			
GENERAL MAINT.	5% CAPITAL COST (187,525)	9,376	
MAINT. SUPPLIES	48,000 LB × 1/5 YR × $.50/LB	4800	
DIRECT LABOR:	.5 HR/SHIFT × 730 SHIFT/YR × $4.00/HR	1460	
SUPERVISION:	10% DIRECT LABOR	146	
DIRECT MFG. COST		34,652	
PAYROLL OVERHEAD:	30% DIRECT LABOR	438	
PLANT OVERHEAD:	50% DIRECT LABOR	730	
PACKAGING:		–	
SHIPPING:		–	
INDIRECT MFG. COST		1168	
DEPRECIATION:	10% CAPITAL COST (190,325)	19033	
PROPERTY TAXES:	1% CAPITAL COST (190,325)	1903	
INSURANCE:	0.5% CAPITAL COST (187,525)	938	
FIXED MFG COST		21,874	
TOTAL PLANT LEVEL COST		57,694	
CORPORATE OVERHEAD	3% TOTAL PLANT LEVEL COST	1730	
TOTAL MFG COST		59,424	
	Say	59,400	.017

* CASE EVALUATED IS THERMAL INCINERATION

MANUFACTURING ESTIMATE - OVEN EXHAUST CONTROL SCHEME

CONTROL PROCESS: ADSORPTION WITH INCINERATION & PRI. HT. RECOVERY ~ OVEN EXHAUST: 20,000 SCFM (25% LEL)

PROCESS OPERATING TIME: 2 SHIFTS/DAY 365 DAYS/YR 5840 HR/YR

ITEM	DESCRIPTION	COST $/YR	COST $/M SCF
RAW MATERIALS			
UTILITIES:			
COOLING WATER	$.03/10³ GAL. × 53,500 GPH × 5840 HR/YR	9400	
STEAM	$1.00/10³ LB × 2220 LB/HR × 5840 HR/YR	12,940	
NATURAL GAS	$.60/10⁶ BTU		
ELECTRICITY	$.015/KWH × [illegible] KW/HR × 5840 HR/YR × (125-86)	13,750	
MAINTENANCE:			
GENERAL MAINT.	5% CAPITAL COST (316,565)	15,828	
MAINT. SUPPLIES	[illegible] LBS × 1/5 YR × $.5/LB	3000	
DIRECT LABOR:	½ HR/SHIFT × 730 SHIFTS/YR × $4.00/HR	1460	
SUPERVISION:	10% DIRECT LABOR	146	
DIRECT MFG. COST		63524	
PAYROLL OVERHEAD	30% DIRECT LABOR	438	
PLANT OVERHEAD	50% DIRECT LABOR	730	
PACKAGING:		-	
SHIPPING:		-	
INDIRECT MFG. COST		1168	
DEPRECIATION:	10% CAPITAL COST (321,315)	32,132	
PROPERTY TAXES:	1% CAPITAL COST (321,315)	3213	
INSURANCE:	0.5% CAPITAL COST (316,565)	1,582	
FIXED MFG COST		36,927	
TOTAL PLANT LEVEL COST		101,619	
CORPORATE OVERHEAD	3% TOTAL PLANT LEVEL COST	3,049	
TOTAL MFG COST		104,668	
	SAY	104,700	.015

* CASE EVALUATED IS THERMAL INCINERATION

MANUFACTURING ESTIMATE - OVEN EXHAUST CONTROL SCHEME

CONTROL PROCESS: ABSORPTION WITH* INCINERATION & SEC. HT. RECOVERY ON OVEN EXHAUST: 1000 SCFM.

PROCESS OPERATING TIME: 2 $\frac{\text{SHIFTS}}{\text{DAY}}$ 365 $\frac{\text{DAYS}}{\text{YR}}$ 5840 $\frac{\text{HR}}{\text{YR}}$ (25% LEL)

ITEM	DESCRIPTION	COST $/YR	COST $/MSCF
RAW MATERIALS			
UTILITIES:			
COOLING WATER	$.03/10³ GAL × 2 [illegible] GPM × 5840 HR/YR	470	
STEAM	$1.00/10³ LB × 111 LB/HR × 5840 HR/YR	647	
NATURAL GAS	$.60/10⁶ BTU —		
ELECTRICITY	$.015/KWH × .746 KW/HP × 5840 HR/YR × (15 + .86(10))	1540	
MAINTENANCE:			
GENERAL MAINT.	5% CAPITAL COST (87,450)	4372	
MAINT. SUPPLIES:	5600 LB × 1/5 YR × $.50/LB	560	
DIRECT LABOR:	.5 HR/SHIFT × 730 SHIFT/YR × $4.00/HR	1460	
SUPERVISION:	10% DIRECT LABOR	146	
DIRECT MFG. COST		9195	
PAYROLL OVERHEAD	30% DIRECT LABOR	438	
PLANT OVERHEAD:	50% DIRECT LABOR	730	
PACKAGING:		—	
SHIPPING:		—	
INDIRECT MFG. COST		1168	
DEPRECIATION:	10% CAPITAL COST (88,750)	8875	
PROPERTY TAXES:	1% CAPITAL COST (88,750)	888	
INSURANCE:	0.5% CAPITAL COST (87,450)	437	
FIXED MFG COST		10,200	
TOTAL PLANT LEVEL COST		20,563	
CORPORATE OVERHEAD	3% TOTAL PLANT LEVEL COST	617	
TOTAL MFG COST		21,180	
	NAT. GAS FUEL SAVINGS: (@ OVEN) LESS	1240	
	$.352 \times 10^6 \frac{\text{BTU}}{\text{HR}} \times 5840 \frac{\text{HR}}{\text{YR}} \times \frac{\$.60}{10^6 \text{BTU}} = \$1240/\text{YR}$	$19,900	.0862

* CASE EVALUATED IS THERMAL INCINERATION

MANUFACTURING ESTIMATE - OVEN EXHAUST CONTROL SCHEME

CONTROL PROCESS: ABSORPTION WITH* INCINERATION & SEC. HT. RECOVERY ~ OVEN EXHAUST 10,000 SCFM.

PROCESS OPERATING TIME: 2 SHIFTS/DAY 365 DAYS/YR 5840 HR/YR (25% LEL)

ITEM	DESCRIPTION	COST	
		$/YR	$/M SCF
RAW MATERIALS			
UTILITIES:			
COOLING WATER	$.03/$10^3$ GAL. × 26,750 GPH × 5840 HR/YR	4700	
STEAM	$1.00/$10^3$ LB × 1110 LB/HR × 5840 HR/YR	6470	
NATURAL GAS	$.60/$10^6$ Btu		
ELECTRICITY	$.015/KWH × .746 KW/HP × 5840 HR/YR × (75 + .86(100))	10500	
MAINTENANCE:			
GENERAL MAINT.	5% CAPITAL COST (236,525)	11826	
MAINT. SUPPLIES	48,000 LB × 1/5 YR × $.50/LB	4800	
DIRECT LABOR:	.5 HR/SHIFT × 730 SHIFT/YR × $4.00/HR	1460	
SUPERVISION:	10% DIRECT LABOR	146	
DIRECT MFG. COST		39,902	
PAYROLL OVERHEAD	30% DIRECT LABOR	438	
PLANT OVERHEAD:	50% DIRECT LABOR	730	
PACKAGING:		-	
SHIPPING:		-	
INDIRECT MFG. COST		1168	
DEPRECIATION:	10% CAPITAL COST (239,875)	23,988	
PROPERTY TAXES:	1% CAPITAL COST (239,875)	2399	
INSURANCE:	0.5% CAPITAL COST (236,525)	1182	
FIXED MFG COST		27,469	
TOTAL PLANT LEVEL COST		68,539	
CORPORATE OVERHEAD	3% TOTAL PLANT LEVEL COST	2056	
TOTAL MFG COST		70,595	
	NATURAL GAS FUEL SAVINGS: (@ OVEN) LESS	12,400	
		58,195	
	$3.52 \times 10^6 \frac{Btu}{HR} \times 5840 \frac{HR}{YR} \times \frac{\$.60}{10^6 Btu} = 12,400$ SAY	58,200	.0166

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* CASE EVALUATED IS THERMAL INCINERATION

MANUFACTURING ESTIMATE - OVEN EXHAUST CONTROL SCHEME

CONTROL PROCESS: ADSORPTION WITH* INCINERATION & SEC. HT. RECOVERY ON OVEN EXHAUST: 20,000 SCFM

PROCESS OPERATING TIME: 2 SHIFTS/DAY 365 DAYS/YR 5840 HR/YR (25% LEL)

ITEM	DESCRIPTION	COST	
		$/YR	$/M SC
RAW MATERIALS			
UTILITIES:			
COOLING WATER	$.03/10³ GAL × 53,500 GPH × 5840 HR/YR	9400	
STEAM	$1.00/10³ LB × 2220 LB/HR × 5840 HR/YR	12940	
NATURAL GAS	$.60/10⁶ Btu		
ELECTRICITY	$.015/KWH × .746 KW/HP × 5840 HR/YR × (125 + .96(200))	19,400	
MAINTENANCE:			
GENERAL MAINT.	5% CAPITAL COST (392,565)	19,600	
MAINT. SUPPLIES	80,000 LB × 1/5 YR × $.50/LB	8,000	
DIRECT LABOR:	.5 HR/SHIFT × 730 SHIFT/YR × $4.00/HR	1,460	
SUPERVISION:	10% DIRECT LABOR	146	
DIRECT MFG. COST		70,946	
PAYROLL OVERHEAD:	30% DIRECT LABOR	438	
PLANT OVERHEAD:	50% DIRECT LABOR	730	
PACKAGING:		–	
SHIPPING:		–	
INDIRECT MFG. COST		1168	
DEPRECIATION:	10% CAPITAL COST (398,465)	39,846	
PROPERTY TAXES:	1% CAPITAL COST (398,465)	3985	
INSURANCE:	0.5% CAPITAL COST (392,565)	1963	
FIXED MFG COST		45794	
TOTAL PLANT LEVEL COST		117,908	
CORPORATE OVERHEAD	3% TOTAL PLANT LEVEL COST	3,537	
TOTAL-MFG COST		121,445	
	NATURAL GAS FUEL SAVINGS: (@ OVEN) LESS	24,800	
	7.05 × 10⁶ Btu/HR × 5840 HR/YR × $.60/10⁶ Btu = $24,800	96,645	
	SAY	96,600.	.0138

MANUFACTURING ESTIMATE - OVEN EXHAUST CONTROL SCHEME

CONTROL PROCESS: ADSORPTION AND THERMAL INCINERATION ~ PROCESS RATE = 1000 SCF
FROM OVEN
PROCESS OPERATING TIME: 5840 $\frac{HR}{YEAR}$ (TRACE SOLVENT W/CATALYST POISON)

ITEM	DESCRIPTION	COST	
		$/YR	$/MSCF
RAW MATERIALS			
UTILITIES:			
COOLING WATER	$.03/10³ GAL. × 2.675×10³ GAL/HR × 5840 HR/YR	470	
STEAM	$1.00/10³ LB × 2.61 LB/HR × 5840 HR/YR	15	
NATURAL GAS	$.60/10⁶ BTU		
ELECTRICITY	$.015/KWH × .746 KW/HP [15(5840) − 3(105)]	980	
MAINTENANCE:			
GENERAL MAINT.	5% CAPITAL COST (65,800)	3290	
MAINT. SUPPLIES	1860 LB × 1/5 YR × $.50/LB	186	
DIRECT LABOR:	.5 HR/SHIFT × 730 SHIFT/YEAR × $4.00/HR	1460	
SUPERVISION:	10% DIRECT LABOR	146	
DIRECT MFG. COST		6547	
PAYROLL OVERHEAD	30% DIRECT LABOR	438	
PLANT OVERHEAD:	50% DIRECT LABOR	730	
PACKAGING:		–	
SHIPPING:		–	
INDIRECT MFG. COST		1168	
DEPRECIATION:	10% CAPITAL COST (66,790)	6679	
PROPERTY TAXES:	1% CAPITAL COST (66,790)	668	
INSURANCE:	0.5% CAPITAL COST (65,800)	329	
FIXED MFG COST		7676	
TOTAL PLANT LEVEL COST		15391	
CORPORATE OVERHEAD	3% TOTAL PLANT LEVEL COST	462	
TOTAL MFG COST		15853	
	SAY	15,900	.0453

MANUFACTURING ESTIMATE - OVEN EXHAUST CONTROL SCHEME

CONTROL PROCESS: ADSORPTION AND THERMAL INCINERATION ~ PROCESS RATE = 10,000 SCFM FROM OVEN

PROCESS OPERATING TIME: 5840 HR/YEAR

(TRACE SOLVENT w/CATALYST POISON)

ITEM	DESCRIPTION	COST	
		$/YR	$/M SCF
RAW MATERIALS			
UTILITIES:			
COOLING WATER	$ .03/10³ GAL × 26.75 × 10³ GAL/HR × 5840 HR/YR	4690	
STEAM	$ 1.00/10³ LB × 26.1 LB/HR × 5840 HR/YR	153	
NATURAL GAS	$ .60/10⁶ BTU		
ELECTRICITY	$ .015/KWH × .746 KW/HP × [75 (5840) + 3 (1060)]	4920	
MAINTENANCE:			
GENERAL MAINT.	5% CAPITAL COST (128,225)	6410	
MAINT. SUPPLIES	16,000 LB × 1/5 YR × $ .50/LB	1600	
DIRECT LABOR:	.5 HR/SHIFT × 730 SHIFT/YEAR × $4.00/HR	1460	
SUPERVISION:	10% DIRECT LABOR	146	
DIRECT MFG. COST		19,379	
PAYROLL OVERHEAD:	30% DIRECT LABOR	438	
PLANT OVERHEAD:	50% DIRECT LABOR	730	
PACKAGING:		–	
SHIPPING:		–	
INDIRECT MFG. COST		1168	
DEPRECIATION:	10% CAPITAL COST (130,150)	13015	
PROPERTY TAXES:	1% CAPITAL COST (130,150)	1302	
INSURANCE:	0.5% CAPITAL COST (128,225)	641	
FIXED MFG COST		14958	
TOTAL PLANT LEVEL COST		35505	
CORPORATE OVERHEAD	3% TOTAL PLANT LEVEL COST	1065	
TOTAL-MFG COST		36,600	.010

MANUFACTURING ESTIMATE - OVEN EXHAUST CONTROL SCHEME

CONTROL PROCESS: ABSORPTION AND THERMAL INCINERATION ~ PROCESS RATE = 20,000 SCFM FROM OVEN

PROCESS OPERATING TIME: 5840 HR/YEAR (TRACE SOLVENT w/CATALYST POISON)

ITEM	DESCRIPTION	COST	
		$/YR	$/M SCF
RAW MATERIALS			
UTILITIES:			
COOLING WATER	$.03/10³ GAL. × 53.5×10³ GAL/HR × 5840 HR/YR	9400	
STEAM	$1.00/10³ LB × 52.2 LB/HR × 5.840×10³ HR/YR	316	
NATURAL GAS	$.60/10⁶ Btu		
ELECTRICITY	$.015/KWH × .746 KW/HP × [5840 × 125 + 3(2110)]	8200	
MAINTENANCE:			
GENERAL MAINT.	5% CAPITAL COST (238,315)	11915	
MAINT. SUPPLIES	26,600 LB × 1/5 YR × $.50/LB	2660	
DIRECT LABOR:	.5 HR/SHIFT × 730 SHIFT/YEAR × $4.00/HR	1460	
SUPERVISION:	10% DIRECT LABOR	146	
DIRECT MFG. COST		34097	
PAYROLL OVERHEAD	30% DIRECT LABOR	438	
PLANT OVERHEAD:	50% DIRECT LABOR	730	
PACKAGING:		–	
SHIPPING:		–	
INDIRECT MFG. COST		1168	
DEPRECIATION:	10% CAPITAL COST (241,890)	24189	
PROPERTY TAXES:	1% CAPITAL COST (241,890	2419	
INSURANCE:	0.5% CAPITAL COST (238,315)	1192	
FIXED MFG COST		27800	
TOTAL PLANT LEVEL COST		63065	
CORPORATE OVERHEAD	3% TOTAL PLANT LEVEL COST	1892	
TOTAL-MFG COST		64957	
	SAY	65,000	.0093

C-52

July 26, 1971

RECEIVED
AUG -4 1971
Singmaster & Breyer, Inc.

Mr. Sam Martin
Singmaster & Breyer
235 East 42nd Street
New York, New York 10017

Dear Sam:

This letter will confirm our recent conversation with regard to solvent recovery of a hexane benezine stream at 100°F in atmospheric pressure.

Enclosed are adsorbtion isotherms for hexane and benezine which should be of valuable assistance to you in designing this unit as well as some other information which will give you a good background on adsorption systems. Normally on such a solvent system a working capacity of 10% is used for design purposes although I believe you will find a higher carbon capacity indicated from the adsorption isotherms. If you prefer to use this figure then use a safety factor of two to go from the theoretical capacity to the working capacity.

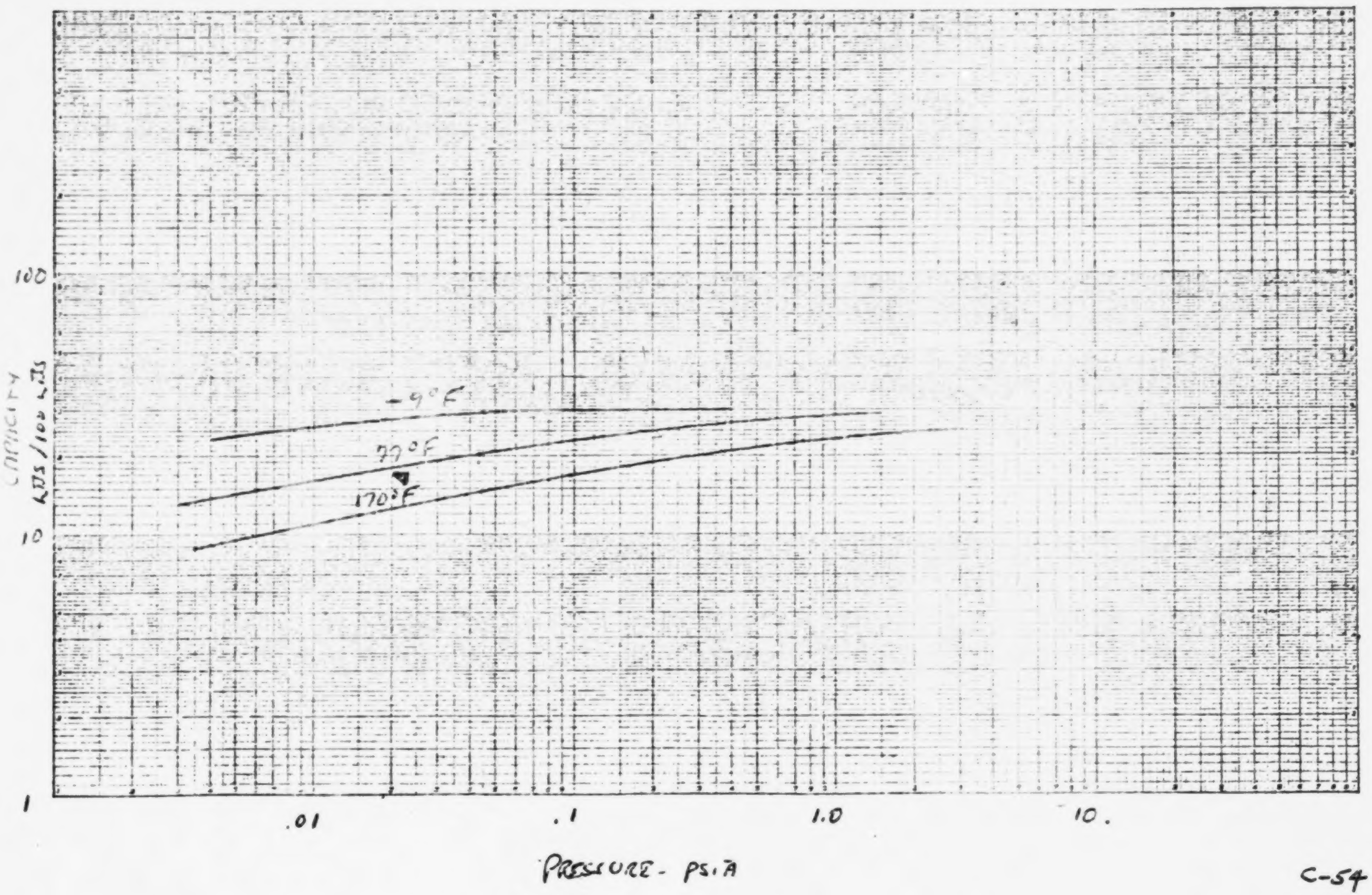
Regeneration of such a system is usually done by steam and the rule of thumb is that 3 to 5 pounds of steam is required per pound of solvent adsorbed on the carbon. Of course this is always a function of heat loss and the surrounding conditions hence the range of steam requirement.

With regard to the activated carbon seminar I will try to set something up sometime in the near future probably immediately after office hours preferably in one of your conference rooms and I hope that you can attend and will also encourage several of your colleagues to attend since we feel it is a worthwhile program.

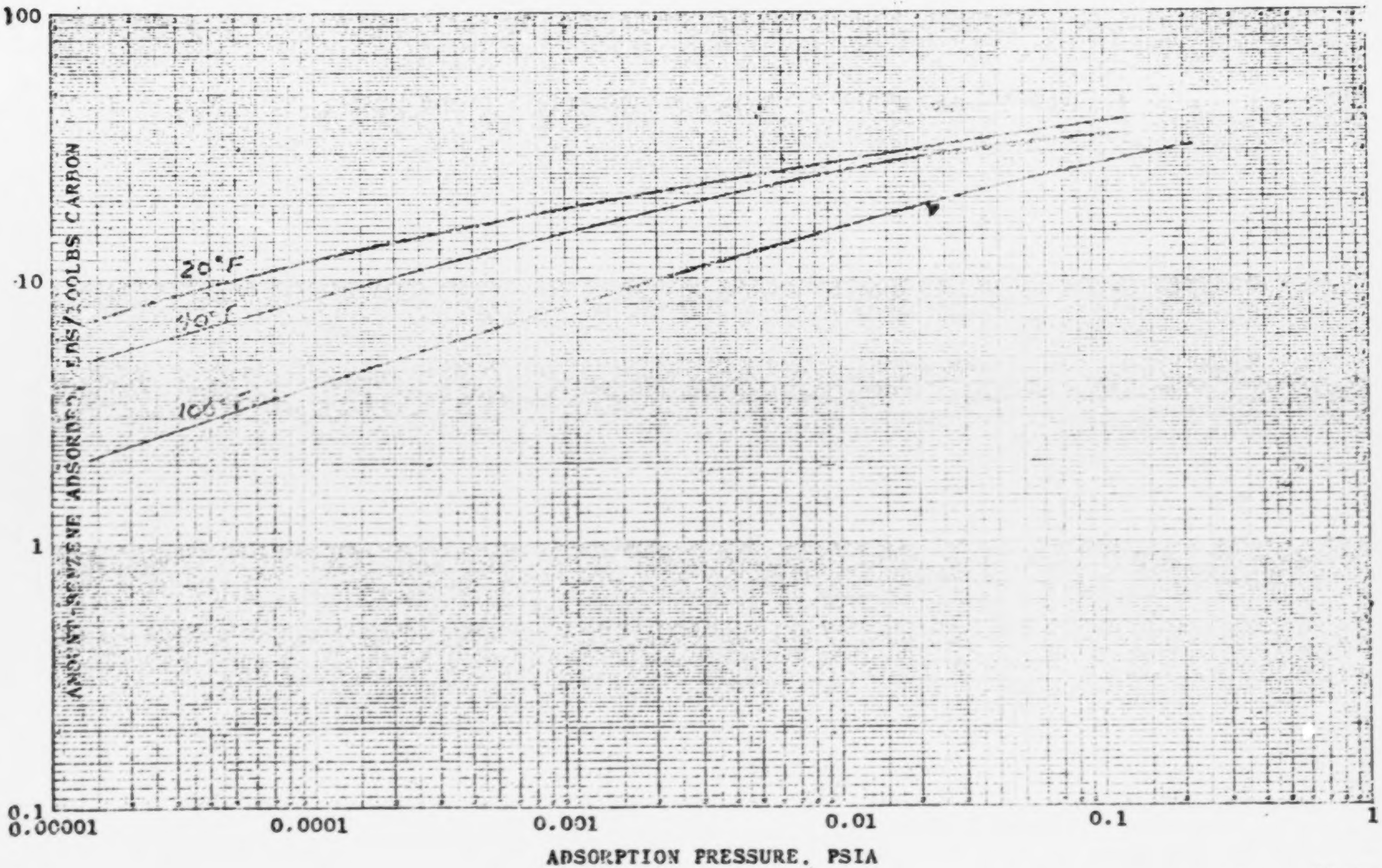
If I can be of any further assistance to you in this project or if you need additional information please contact either myself or Mr. T. A. Dixon at our East Orange office. Thank you very much for this opportunity to be of service.

Very truly yours,

n-HEXANE ADSORPTION ISOTHERMS ON BPL CARBON



ESTIMATED ADSORPTION OF BENZENE ON BPL ACTIVATED CARBON



C-55
VHM
1985

July 29, 1971

RECEIVED
AUG -2 1971
Singmaster & Breyer, Inc.

Mr. Sam Martin
Singmaster & Beyer Co.
235 East 42nd Street
New York, New York 10017

Dear Mr. Martin,

As I mentioned to you in our telephone conversation of this afternoon, the equilibrium capacity of our Grade 256, 4 x 10 for the benzene-n, hexane-air mixture was 23% w/w. The conditions studied were as follows:

Concentration: 0.15% V/V benzene
0.15% V/V n, hexane
0.70% V/V air

Bed Temperature: 100° ± 2°F

Bed Dimensions: 3" diameter x 3" height

Flow Rate: 20 L/min.

Because the superficial velocity though the bed was low, and because the bed was relatively shallow, wavefront data (breakthrough and capacity at breakthrough) were not determined. However breakthrough time was in excess of 6 hours and capacity at this point was probably 18-20% w/w.

The carbon was steamed for 15 minutes at 275°F (45 PSIA). The bulk of the adsorbate was stripped after five minutes; this would result in a steam solvent ratio of 4:1. As I mentioned, this ratio should decrease markedly under plant conditions, where steam of much higher pressure (≥ 150 PSIG) could be used.

The relative concentrations of the benzene and hexane on the carbon were determined by cold-trapping off the adsorbate. The adsorbed phase was found to be hexane rich, the benzene amounting to 30% of the desorbed material, indicating preferential adsorption of the hexane.

I hope these data are useful to you in designing your solvent recovery system. If you have any further questions regarding Grade 256 or any of our other activated carbons, do not hesitate to call me.

Sincerely.

July 19, 1971

Singmaster & Breyer
235 E. 42nd Street
New York City, New York 10017

RECEIVED
JUL 21 1971
Singmaster & Breyer, Inc.

Attention: Mr. Samuel Martin

Gentlemen:

We are pleased to confirm the following approximate prices for a 50/50 blend of hexane and benzene at 25% of the L.E.L. at 375°F.

1000 cfm	$35,000	+	$10,000 installation
10,000 cfm	$70,000	+	$15,000 installation
20,000 cfm	$110,000	+	$30,000 installation

These prices are based on our standard compact design which in sizes through 10,000 cfm are skid-mounted shop-assembled units. Larger sizes must be field assembled.

We enclose a copy of our brochures which give further information on our various sizes and their capabilities. We regret that we are unable to give you a detailed price breakdown of the various items comprising the system.

Very truly yours,

APPENDIX D

INCINERATION-ABSORPTION

AND

SCRUBBING-ABSORPTION

TABLE OF CONTENTS

PROCESS CONCEPT D-1
INCINERATION-ABSORPTION
  Process Calculations D-3
  Installed Cost Estimates D-7
  Operating Cost Estimates D-10
SCRUBBING-ABSORPTION
  Installed Cost Estimates D-13
  Operating Cost Estimates D-17

PROCESS CONCEPT FOR CONTROL OF HYDROCARBON EMISSIONS BY INCINERATION-ABSORPTION SYSTEMS AND SCRUBBING-ABSORPTION SYSTEMS

INCINERATION-ABSORPTION

The economic evaluation of incineration of waste organics followed by absorption of soluble gases and particulates is based on the industrial case history described in Appendix E. A waste liquid stream of kerosene containing DDT is incinerated by a direct-flame incinerator and the incinerator gases are passed through a packed absorption tower to remove soluble gases and particulates. In the particular example studied, HCl was the principal waste gas collected in the absorber.

Three levels of operation were considered: 100 gph (2,000 scfm); 500 gph (11,800 scfm); and 1,000 gph (23,500 scfm). Operating costs were based on a 2 shift/day operation, 330 days/year.

SCRUBBING-ABSORPTION

The economic evaluation of wet scrubbing absorption of soluble organic waste gases was adapted from an actual installation for the control of waste gases from specialty organic chemical synthesis. Isopropanol vapors were used to develop the design basis for the absorber, although other less volatile organics are known to exist in the waste stream.

The basic economic study was made at the actual plant capacity. Additional capacity levels were estimated by employing the "six-tenths factor rule". Operating costs were based on a 2 shift/day, 330 day/year operation.

Waste Water Disposal

Rather than attempt to estimate overage waste water disposal costs (e.g., negotiated rate for sewerage), the operating cost calculations considered a higher initial water cost (process water instead of cooling water) and assumed no disposal costs. For specific cases, the trade-off of initial water costs and disposal costs should be treated on an individual basis. In this generalized economic study, detailed treatment of such trade-offs were not made because of the strong dependency on local plant conditions. However, the use of a higher initial water cost should approximately balance off the cost of disposal.

SINGMASTER & BREYER
CHEMICAL & METALLURGICAL PROCESS ENGINEERS

COMPUTATION SHEET

J. O. No. PS-228
SHEET No. D-3 OF
DATE 9/28/71
COMP. BY STM C'K'D BY

NAME OF COMPANY MSA RESEARCH CORP

SUBJECT ECONOMIC EVALUATION ~ PATENT DEVELOPMENT ASSOCIATES, INC. (PDA) ~ INCINERATOR/ABSORBER CASE HISTORY NO 1 (IN FINAL DRAFT REPORT TO MSA RESEARCH CORP)

BASIS: CASE HISTORY RATES
FEED: @ 668 LB/HR.
INCINERATOR

	WT%	lb/hr	M.W's	MOLE/HR	Cl lb-ATOMS/HR
DDT: $C_{14}H_9Cl_5$	5	33.4	354.5	.0944	.0472
KEROSINE: $C_{.85}H_{.15}$	95	634.6	10.35	61.3	
		668		61.3944	

EXHAUST
INCINERATOR

COMPONENT	MOLE/HR	LB/HR
CO_2	54.2	2385
N_2	254.5	7120
O_2	11.3	362
NO	.0427	1.2
INERT	320.0427	9868.2
HCl	.0472	1.72
TOTAL DRY	320.0899	9869.92
H_2O	4.85	87.3
	324.9399	

ANALYSIS OF MSA CASE - (NO & DDT NEGLECTED BELOW)

STOICHIOMETRIC VALUES:

$$\overset{635}{C_{.85}H_{.15}} + \overset{1740}{.887\,O_2} = \overset{2290}{.85\,CO_2} + \overset{82.1}{.075\,H_2O}$$

10.4 23.4 37.4 1.35

N_2: $\frac{1740}{32} \times \frac{79}{21} \times 28 = 5720$ LB

EXCESS AIR:

O_2 = 362 lb. N_2 $\frac{362}{32} \times \frac{79}{21} \times 28 = 1190$ lb

SINGMASTER & BREYER
CHEMICAL & METALLURGICAL PROCESS ENGINEERS

COMPUTATION SHEET
J. O. No. PS-228
Sheet No. D-4 of
Date 9/28/71
Comp. by STM C'k'd by

Name of Company MSA Research Corp.
Subject Economic Evaluation. (PDA Case History)

Combustion Products (NO & DDT Neglected)

Component	LB.
CO_2	2290
N_2	6910
O_2	362
H_2O	82.1

Check is Close Enough

$\% XS\ Air \cong \frac{362}{1740} \times 100 \cong 20\%$

Moles In

$C_{.85}H_{.15}$	61.3
$C_{14}H_9Cl_5$	.1
Air	310.0
	371.4

Moles Out

	PDA	Check
CO_2	54.2	52.0
N_2	254.5	246.0
O_2	11.3	11.3
NO	.0427	.0427
HCl	.0472	.0472
H_2O	4.85	4.55
	324.9399	313.9399

Checked value OK.

Incinerator to be sized on basis of volume in

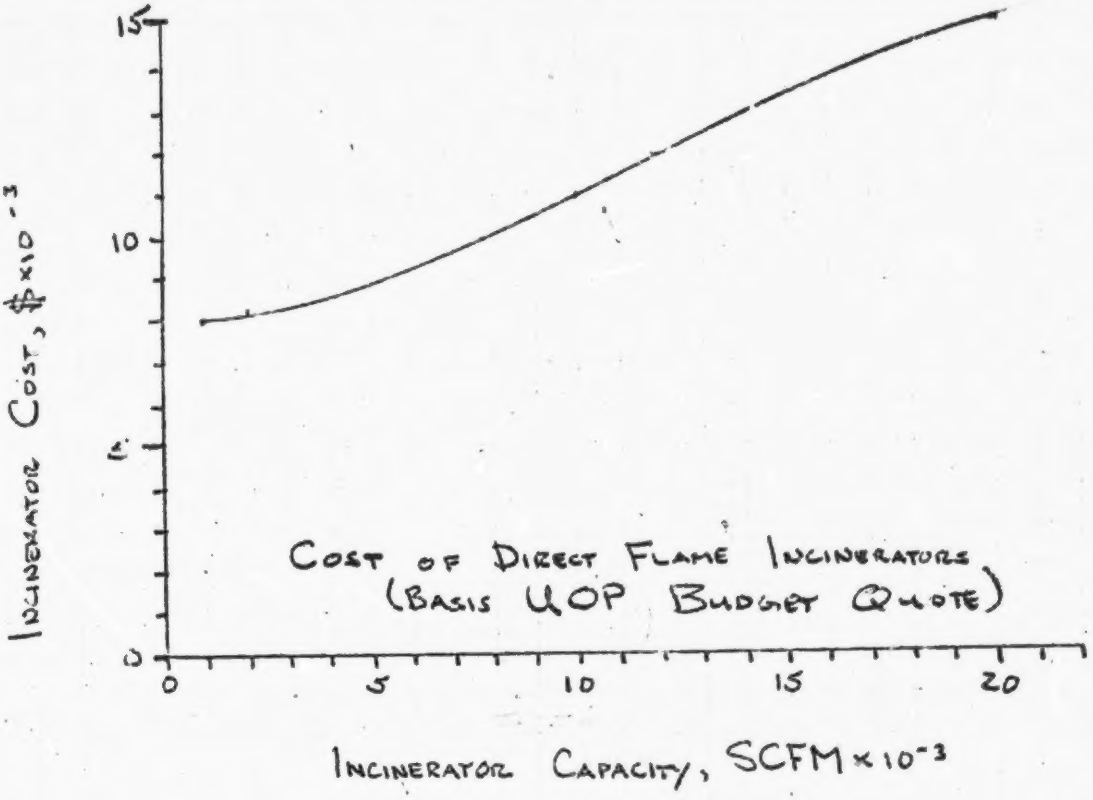
$371.4\,(359)\,\frac{520}{492}\left(\frac{1}{60}\right) = 2350$ SCFM IN

$\frac{325}{371} \times 2350 = 2050$ Out

COMPUTATION SHEET
J. O. No. PS-228
SHEET No. D-5 OF
DATE 9/28/71
COMP. BY STM C'K'D BY

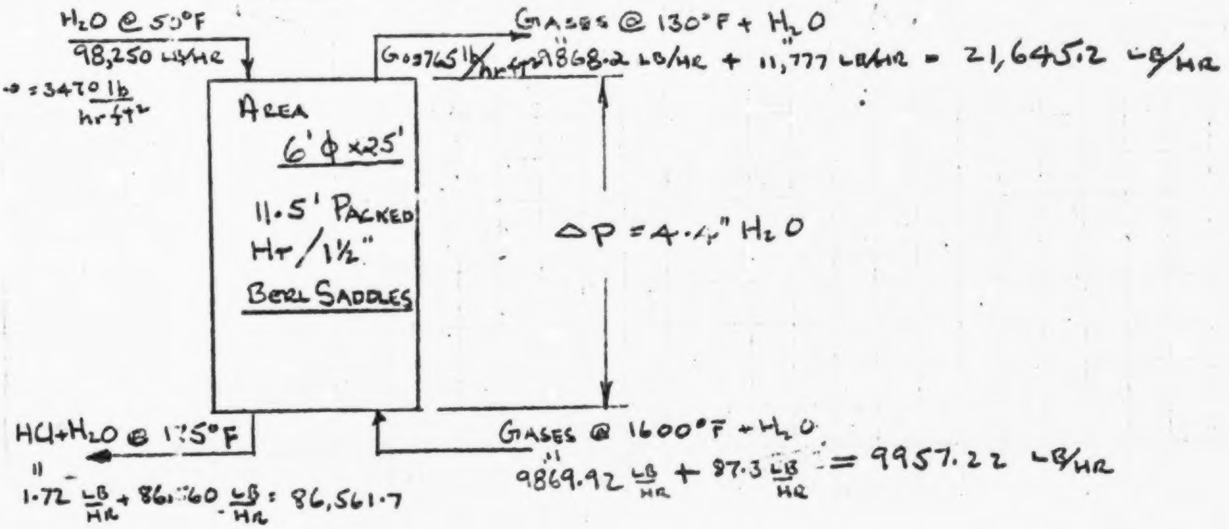
NAME OF COMPANY MSA Research Corp

SUBJECT Economic Evaluation (PDA Case History)



Cost of Direct Flame Incinerators
(Basis UOP Budget Quote)

PDA Case History - Absorber
(Base Case)


H₂O @ 50°F
98,250 LB/HR
=3470 lb/hr ft²
Area
6' φ × 25'
11.5' Packed Ht/1½" Berl Saddles
Gases @ 130°F + H₂O
G=765 lb/hr ft²
9868.2 LB/HR + 11,777 LB/HR = 21,645.2 LB/HR
ΔP = 4.4" H₂O
HCl + H₂O @ 175°F
1.72 LB/HR + 86,560 LB/HR = 86,561.7
Gases @ 1600°F + H₂O
9869.92 LB/HR + 87.3 LB/HR = 9957.22 LB/HR

SINGMASTER & BREYER
CHEMICAL & METALLURGICAL PROCESS ENGINEERS

COMPUTATION SHEET
J. O. No. PS-228
SHEET No. D-6 OF
DATE 9/28/71
COMP. BY STM C'K'D BY

NAME OF COMPANY MSA RESEARCH CORP.
SUBJECT ECONOMIC EVALUATION (PDA CASE HISTORY)

ASSUME: COMBUSTION/ATOMIZING AIR ARE HANDLED BY BLOWER

BLOWER:

DESIGN PRESS: 8.8" H_2O

VOLUME = $\frac{9012}{29} \times \frac{359}{60} \times \frac{520}{492} = 1980$ SCFM SAY 2000 SCFM

EFFICIENCY = 60%

$\frac{8.8}{12} \times \frac{62.4 \times 2000}{33,000} \times \frac{1}{.6} = 4.64$ SAY 5HP

STACK AREA = $\frac{21,645 \times 47}{3600 \times 35} = 8.1$

WATER USE = 11,800 GPH

DIAM = 3' HT = 30

500 GAL/HR WASTE:	1000 GAL/HR WASTE
INCINERATOR IN ≅ 11,800 SCFM	INCINERATOR IN ≅ 23,500 SCFM
FAN HP = 25	FAN HP = 50
H_2O USE = 59,000 GPH	H_2O USE = 118,000 GPH
STACK:	
STACK VELOCITY ~ 35 FT/SEC	
STACK ~ 5ϕ ×50	STACK ~ 7'ϕ ×70

CONSTRUCTION COST ESTIMATE

SINGMASTER & BREYER

CUSTOMER MSA Research Corp

LOCATION Evans City, Pa

PROJECT PS-228

DESCRIPTION Incineration/Absorption for Disposal of DDT & Kerosine Waste

Capacity: 100 GPH/2000 SCFM

PROP. NO.

CONT. NO.

MADE BY

APPROVED

ACCOUNT NUMBER	ITEM & DESCRIPTION	QUANTITY	UNIT	UNIT COSTS			ESTIMATED COST CENTS OMITTED			
				LABOR	SUB CONTR	MAT'L	LABOR	SUB CONTRACTS	MATERIALS	TOTAL
	Incinerator, Type: Direct Flame Capacity: 100 GPH/2000 SCFM									8,200 –
	Combustion Air Fan, Type: Centrifugal Capacity: 2000 SCFM @ 8.8" S.P. @ 5 HP									770 –
	Absorber: Mild Steel 6'φ×26'H×¼"Tk., Brick Lined, Packed 11'-6" with 1½" Ceramic Berl Saddles									14,500 –
	Stack - 3'φ×30'H Carbon Steel/Epoxy Coated									3,300 –
	Holding Tank (2000 Gal)									2,200 –
	Pump, C.I. Const, 10GPM @ 30' TDH & 3HP									500 –
								Equipment	Subtotal	29,470 -
	Installation: (@ 100% Equip. Cost Includes) Excavation & Foundations Erection, Piping, Ductwork, Insulation Electrical, Instrumentation Painting, Cleanup									29,470 -
								Installed	SubTotal	58,940 –
	Interest On Investment During Const (2 Months @ Prime Rate, 6%)									590 –
								Total		59530 –
CODE									Say	60,000 –

(E 153)

DATE ______ REVISION NO. ______ REVISION DATE ______ PAGE NO. D-7

CONSTRUCTION COST ESTIMATE

SINGMASTER & BREYER

CUSTOMER MSA Research Corp

LOCATION Evans City, Pa

PROJECT PS-228

DESCRIPTION Incineration / Absorption for Disposal of DDT & Kerosine Waste

Capacity: 500 GPH / 11,800 SCFM

PROP. NO.

CONT. NO.

MADE BY

APPROVED

ACCOUNT NUMBER	ITEM & DESCRIPTION	QUANTITY	UNIT	UNIT COSTS			ESTIMATED COST CENTS OMITTED			
				LABOR	SUB CONTR	MAT'L	LABOR	SUB CONTRACTS	MATERIALS	TOTAL
	Incinerator, Type: Direct Flame Capacity: 500 GPH / 11,800 SCFM									12,000 –
	Combustion Air Fan, Type: Centrifugal Capacity: 10,000 SCFM @ 8.8" SP @ 25 HP									2020 –
	Absorber: Mild Steel, Brick Lined Packed with 1½" Berl Saddles									38,000 –
	Stack - 5'φ x 50'H Carbon Steel									9150 –
	Holding Tank (10,000 gal)									5800 –
	Pump, C.I. Const, 10 GPM @ 30' TDH & 3 HP									500 –
								Equipment	Subtotal	67,470 –
	Installation: (@100% Equipment Cost) Includes: Excavation, Foundations, Erection, Piping, Ductwork, Insulation, Electrical, Instrumentation, Painting & Clean-Up									67,470 –
								Installed	Subtotal	134,940 –
	Interest On Investment During Const (2 Months @ Prime Rate, 6%)									1,350 –
								Total		136,290 –
									Say	136,000 –

CODE

(E 153)

DATE ______ REVISION NO. ______ REVISION DATE ______ PAGE NO. D-8

CONSTRUCTION COST ESTIMATE

SINGMASTER & BREYER

CUSTOMER MSA Research Corp

LOCATION Evans City, Pa

PROJECT PS-228

DESCRIPTION Incineration/Absorption For Disposal of DDT and Kerosine

Capacity: 1000 GPH/23,500 SCFM

PROP. NO.

CONT. NO.

MADE BY

APPROVED

ACCOUNT NUMBER	ITEM & DESCRIPTION	QUANTITY	UNIT	UNIT COSTS			ESTIMATED COST CENTS OMITTED			
				LABOR	SUB CONTR	MAT'L	LABOR	SUB CONTRACTS	MATERIALS	TOTAL
	Incinerator, Type: Direct Flame Capacity: 1000GPH/23,500 SCFM									16,000 —
	Combustion Air Fan, Type: Centrifugal Capacity: 20,000 SCFM@8.8SP@50HP									3,100 —
	Absorber: Mild Steel, Brick Lined Packed with 1½" Berl Saddles									58,000 —
	Stack - 7'φ x 70'H Carbon Steel									13,200 —
	Holding Tank (20,000 Gal)									8,800 —
	Pump, C.I. Construction, 20GPM@30' TDH @ 7.5HP									750 —
								Equipment	Subtotal	99,850 —
	Installation: (@100% Equipment Cost) Includes: Excavation, Foundations, Erection, Piping, Ductwork, Insulation, Electrical, Instrumentation, Painting & Clean-up									99,850 —
								Installed	Subtotal	199,700 —
	Interest on Investment During Const. (2 Months @ Prime Rate, 6%)									2000 —
								Total		201,700 —
									Say	202,000 —

CODE

(E 153)

DATE ____ REVISION NO. ____ REVISION DATE ____ PAGE NO. D-9

MANUFACTURING ESTIMATE - KEROSINE/DDT DISPOSAL SYSTEM

CONTROL PROCESS: DIRECT FLAME INCINERATION/ABSORPTION - PDA STUDY CASE

PROCESS OPERATING TIME: 330 DAYS/YR; 2 SHIFTS/DAY; 5280 HR/YR

CAPACITY: 100 GPH/2000 SCFM

ITEM	DESCRIPTION	COST	
		$/YR	$/MSCF
RAW MATERIALS			
UTILITIES:			
PROCESS WATER	$ .30/10^3 GAL × 11,800 × 5280 HR/YR	18,700	
COOLING WATER	$ .03/10^3 GAL		
STEAM	$ 1.00/10^3 LB		
NATURAL GAS	$ .60/10^6 Btu		
ELECTRICITY	$ .015/KWH × 8HP × .746 $\frac{KW}{HP}$ × 5280 $\frac{HR}{YR}$	472	
MAINTENANCE:			
GENERAL MAINT.	5% CAPITAL COST (58,940)	2947	
MAINT. SUPPLIES			
DIRECT LABOR	.5 HR/SHIFT × 660 SHIFT/YR × $ 4.00/HR	1320	
SUPERVISION	10% DIRECT LABOR	132	
DIRECT MFG. COST		23,571	
PAYROLL OVERHEAD	30% DIRECT LABOR	396	
PLANT OVERHEAD	50% DIRECT LABOR	660	
PACKING		-	
SHIPPING		-	
INDIRECT MFG. COST		1056	
DEPRECIATION	10% CAPITAL COST (59,530)	5953	
PROPERTY TAXES	1% CAPITAL COST (59,530)	595	
INSURANCE	0.5% CAPITAL COST (58940)	295	
FIXED MAN. COST		6843	
TOTAL PLANT LEVEL COST		31,470	
CORP. OVERHEAD	3% TOTAL PLANT LEVEL COST	944	
TOTAL MFG. COST		32,414	.051/MSCF
		SAY 32,400	.0605/GAL

MANUFACTURING ESTIMATE - KEROSINE /DDT DISPOSAL SYSTEM
CONTROL PROCESS: DIRECT FLAME INCINERATION/ABSORPTION - PDA STUDY CASE
PROCESS OPERATING TIME: 330 DAYS/YR; 2 SHIFTS/DAY; 5280 HR/YR
CAPACITY: 500 GPH/10,000 SCFM

ITEM	DESCRIPTION	COST $/YR	 $/MSCF
RAW MATERIALS			
UTILITIES:			
PROCESS WATER	$ .30/10^3 GAL × 59,000 GPH × 5280 HR/YR	93,000	
COOLING WATER	$ .03/10^3 GAL		
STEAM	$ 1.00/10^3 LB		
NATURAL GAS	$ .60/10^6 BTU		
ELECTRICITY	$ .015/KWH × 28 HP × .746 $\frac{KW}{HP}$ × 5280 $\frac{HR}{YR}$	1650	
MAINTENANCE: GENERAL MAINT. MAINT. SUPPLIES	5% CAPITAL COST (134,940)	6747	
DIRECT LABOR	.5 HR/SHIFT × 660 SHIFT/YR × $ 4.00/HR	1,320	
SUPERVISION	10% DIRECT LABOR	132	
DIRECT MFG. COST		102,849	
PAYROLL OVERHEAD	30% DIRECT LABOR	396	
PLANT OVERHEAD	50% DIRECT LABOR	660	
PACKING		–	
SHIPPING		–	
INDIRECT MFG. COST		1,056	
DEPRECIATION	10% CAPITAL COST (136,290)	13629	
PROPERTY TAXES	1% CAPITAL COST (136,290)	1363	
INSURANCE	0.5% CAPITAL COST (134,940)	675	
FIXED MFG. COST		15,667	
TOTAL PLANT LEVEL COST		119,572	
CORP. OVERHEAD	3% TOTAL PLANT LEVEL COST	3587	
TOTAL MFG. COST		123,159	.033/MSCF
	SAY	123,200	.0466/GAL

MANUFACTURING ESTIMATE - KEROSINE/DDT DISPOSAL SYSTEM

CONTROL PROCESS DIRECT FLAME INCINERATION/ABSORPTION - PDA STUDY CASE

PROCESS OPERATING TIME: 330 DAYS/YR; 2 SHIFTS/DAY; 5280 HR/YR

CAPACITY: 1000 GPH/20,000 SCFM

ITEM	DESCRIPTION	COST $/YR	 $/MSCF
RAW MATERIALS			
UTILITIES:			
PROCESS WATER	$ .30/10³ GAL × 118,000GPH × 5280 HR/YR	187,000	
COOLING WATER	$ .03/10³ GAL		
STEAM	$ 1.00/10³ LB		
NATURAL GAS	$ .60/10⁶ BTU		
ELECTRICITY	$ .015/KWH × 57.5 HP × .746 KW/HP × 5280 HR/YR	3400	
MAINTENANCE:			
GENERAL MAINT.	5% CAPITAL COST (199,700)	9985	
MAINT. SUPPLIES			
DIRECT LABOR	.5 HR/SHIFT × 660 SHIFT/YR × $ 4.00/HR	1320	
SUPERVISION	10% DIRECT LABOR	132	
DIRECT MFG. COST		201,837	
PAYROLL OVERHEAD	30% DIRECT LABOR	396	
PLANT OVERHEAD	50% DIRECT LABOR	660	
PACKING		-	
SHIPPING		-	
INDIRECT MFG. COST		1056	
DEPRECIATION	10% CAPITAL COST (201,700)	20,170	
PROPERTY TAXES	1% CAPITAL COST (201,700)	2017	
INSURANCE	0.5% CAPITAL COST (199,700)	1000	
FIXED MAN. COST		23,187	
TOTAL PLANT LEVEL COST		226,080	
CORP. OVERHEAD	3% TOTAL PLANT LEVEL COST	6780	
TOTAL MFG. COST		232,860	.0314/MSCF
	SAY	232,900	.0441/GAL

CONSTRUCTION COST ESTIMATE

SINGMASTER & BREYER

CUSTOMER MSA Research Corp

LOCATION Evans City, Pa

PROJECT PS-228

DESCRIPTION Scrubbing and Absorption of Reactor Exhaust - For Removal of Solid Particles and Isopropanol

System Capacity: 1000 CFM

PROP. NO.

CONT. NO.

MADE BY

APPROVED

ACCOUNT NUMBER	ITEM & DESCRIPTION	QUANTITY	UNIT	UNIT COSTS			ESTIMATED COST CENTS OMITTED			
				LABOR	SUB CONTR	MAT'L	LABOR	SUB CONTRACTS	MATERIALS	TOTAL
	Venturi Scrubber - 304 SS with Adjustable Throat									5400 —
	Absorbtion Tower - 304 SS 2' ϕ x 14' High									
	Fan - Mild Steel Const. with Protective Coating - Capacity 1000 ACFM @ 60°F @ 42" S.P. 15 HP									
	Centrifugal Pump ~ 304 SS Const. Capacity ~ 20 GPM @ 60' TDH 1.5 HP									
	Instrumentation Land (Existing) Excavation & Foundations Piping, Ductwork, Insulation Painting & Cleanup									5400 —
									Sub-Total	10,800 —
	Interest on Investment During Construction - @ Prime, 6%, Rate for One Month Duration									50 —
									Total	10,850 —
									Say	10,900

CODE

(E 15)

CONSTRUCTION COST ESTIMATE

SINGMASTER & BREYER

CUSTOMER MSA Research Corp.

LOCATION Evans City, Pa.

PROJECT PS-228

DESCRIPTION Scrubbing and Absorption of Reactor Exhaust - For Removal of Solid Particles and Isopropanol

System Capacity : 4000 CFM

PROP. NO.

CONT. NO.

MADE BY

APPROVED

ACCOUNT NUMBER	ITEM & DESCRIPTION	QUANTITY	UNIT	UNIT COSTS			ESTIMATED COST CENTS OMITTED			
				LABOR	SUB CONTR	MAT'L	LABOR	SUB CONTRACTS	MATERIALS	TOTAL
	Venturi Scrubber - 304 SS with Adjustable Throat									12,315 —
	Absorbtion Tower - 304 SS - 4' ϕ × 14' High									
	Fan - Mild Steel Const. with Protective Coating - Capacity: 4000 ACFM @ 60°F @ 42" S.P. ~ 50 HP									
	Centrifugal Pump - 304 SS Const. Capacity: 75 GPM @ 70' TDH ~ 5 HP									
	Instrumentation									
	Land (Existing)									
	Excavation & Foundations									
	Piping, Ductwork, Insulation									12,315 —
	Painting & Clean-up									
									Sub-Total	24,630 —
	Interest on Investment During Construction - @ Prime, 6%, Rate for One Month Duration									120 —
									TOTAL	24,750 —
CODE									SAY	24,800 —

(E 153)

DATE ______ REVISION NO. ______ REVISION DATE ______ PAGE NO. D-14

CONSTRUCTION COST ESTIMATE

SINGMASTER & BREYER

CUSTOMER MSA Research Corp

LOCATION Evans City, Pa.

PROJECT PS-228

DESCRIPTION Scrubbing and Absorption of Reactor Exhaust. For Removal of Solid Particles and Isopropanol

System Capacity: 8000 CFM

PROP. NO.

CONT. NO.

MADE BY

APPROVED

ACCOUNT NUMBER	ITEM & DESCRIPTION	QUANTITY	UNIT	UNIT COSTS			ESTIMATED COST CENTS OMITTED			
				LABOR	SUB CONTR	MAT'L	LABOR	SUB CONTRACTS	MATERIALS	TOTAL
	Venturi Scrubber - 304 SS with Adjustable Throat									18,600 -
	Absorption Tower - 304 SS 6' ϕ x 14' High									
	Fan - Mild Steel Const. with Protective Coating: 8000 CFM @ 60°F @ 42" S.P. ~ 100 HP									
	Centrifugal Pump - 304 SS Const. Capacity: 150 GPM @ 70' TDH ~ 10 HP									
	Instrumentation									
	Land (Existing)									
	Excavation & Foundations									18,600 -
	Piping, Ductwork, Insulation								Sub-Total	37,200 -
	Painting & Clean-up									
	Interest on Investment During Construction - @ Prime, 6%, Rate for One Month Duration									190 -
									Total	37390 -
CODE									Say	37,400 -

(E 153)

DATE ______ REVISION NO. ______ REVISION DATE ______ PAGE NO. D-15

CONSTRUCTION COST ESTIMATE

SINGMASTER & BREYER

CUSTOMER MSA Research Corp

LOCATION Evans City, Pa.

PROJECT PS-228

DESCRIPTION Scrubbing and Absorption of Reactor Exhaust - For Removal of Solid Particles and Isopropanol

System Capacity: 20,000

PROP. NO.

CONT. NO.

MADE BY

APPROVED

ACCOUNT NUMBER	ITEM & DESCRIPTION	QUANTITY	UNIT	UNIT COSTS LABOR	UNIT COSTS SUB CONTR	UNIT COSTS MAT'L	ESTIMATED COST (CENTS OMITTED) LABOR	ESTIMATED COST SUB CONTRACTS	ESTIMATED COST MATERIALS	ESTIMATED COST TOTAL
	Venturi Scrubber - 304 SS with Adjustable Throat									32,600 —
	Absorbtion Tower - 304 SS 8'ϕ × 14' High									
	Fan - Mild Steel Const. with Protective Coating - Capacity 20,000 ACFM @ 60°F @ 42" SP ~ 250HP									
	Centrifugal Pump - 304 SS Const. Capacity ~ 375 GPM @ 70' TDH 25HP									
	Instrumentation Land (Existing) Excavation & Foundations Piping, Ductwork, Insulation Painting & Clean-up									32,600 —
									Sub-Total	65,200 —
	Interest on Investment During Construction - @ Prime, 6%, Rate for One Month Duration									330 —
									Total	65,530 —

CODE

(E 153)

DATE ______ REVISION NO. ______ REVISION DATE ______ PAGE NO. D-16

D-17

MANUFACTURING ESTIMATE-REACTOR EXHAUST STUDY

CONTROL PROCESS: SCRUBBING AND ABSORPTION OF REACTOR VAPORS

PROCESS OPERATING TIME: 330 DAYS/YR; 2 SHIFTS/DAY; 5280 HR/YR

CAPACITY ~ 1000 CFM @ 60°F

ITEM	DESCRIPTION	COST $/YR	 $/MSCF
RAW MATERIALS			
UTILITIES: PROCESS WATER COOLING WATER STEAM NATURAL GAS ELECTRICITY	$ .30/10³ GAL × 300 GPH × 5280 HR/YR $ .03/10³ GAL $ 1.00/10³ LB $ .60/10⁶ Btu $ .015/KWH × 16.5 HP × .746 KW/HP × 5280 HR/YR	475 972	
MAINTENANCE: GENERAL MAINT. MAINT. SUPPLIES	5% CAPITAL (10,800)	540	
DIRECT LABOR	.5 HR/SHIFT × 660 SHIFT/YR × $ 4.00/HR	1320	
SUPERVISION	10% DIRECT LABOR	132	
DIRECT MFG. COST		3439	
PAYROLL OVERHEAD PLANT OVERHEAD PACKING SHIPPING	30% DIRECT LABOR 50% DIRECT LABOR	396 660 - -	
INDIRECT MFG. COST		1056	
DEPRECIATION PROPERTY TAXES INSURANCE	10% CAPITAL COST (10,850) 1% CAPITAL COST (10,850) 0.5% CAPITAL COST (10,800)	1085 108 54	
FIXED MAN. COST		1247	
TOTAL PLANT LEVEL COST		5742	
CORP. OVERHEAD	3% TOTAL PLANT LEVEL COST	172	
TOTAL MFG. COST		5914	
	SAY	5900	.019

MANUFACTURING ESTIMATE - REACTOR EXHAUST STUDY

CONTROL PROCESS: SCRUBBING AND ABSORPTION OF REACTOR VAPORS

PROCESS OPERATING TIME: 330 DAYS/YR; 2 SHIFTS/DAY; 5280 HR/YR

CAPACITY - 4000 CFM @ 60°F

ITEM	DESCRIPTION	COST	
		$/YR	$/MSCF
RAW MATERIALS			
UTILITIES:			
PROCESS WATER	$ .30/10^3 GAL × 1200 GPM × 5280 HR/YR	1900.	
COOLING WATER	$ .03/10^3 GAL	–	
STEAM	$ 1.00/10^3 LB	–	
NATURAL GAS	$ .60/10^6 Btu	–	
ELECTRICITY	$ .015/KWH × .746 $\frac{KW}{HP}$ × 55 HP × 5280 $\frac{HR}{YR}$	3240.	
MAINTENANCE:			
GENERAL MAINT.	5% CAPITAL (24,630)	1232	
MAINT. SUPPLIES			
DIRECT LABOR	.5 HR/SHIFT × 660 SHIFT/YR × $ 4.00/HR	1320	
SUPERVISION	10% DIRECT LABOR	132	
DIRECT MFG. COST		7824	
PAYROLL OVERHEAD	30% DIRECT LABOR	396	
PLANT OVERHEAD	50% DIRECT LABOR	660	
PACKING		–	
SHIPPING		–	
INDIRECT MFG. COST		1056	
DEPRECIATION	10% CAPITAL COST (24,750)	2475	
PROPERTY TAXES	1% CAPITAL COST (24,750)	248	
INSURANCE	0.5% CAPITAL COST (24,630)	123	
FIXED MAN. COST		2846	
TOTAL PLANT LEVEL COST		11,726	
CORP. OVERHEAD	3% TOTAL PLANT LEVEL COST	352	
TOTAL MFG. COST		12,078	
	SAY	12,100	.0095

D-19

MANUFACTURING ESTIMATE - REACTOR EXHAUST STUDY

CONTROL PROCESS: SCRUBBING AND ABSORPTION OF REACTOR VAPORS

PROCESS OPERATING TIME: 330 DAYS/YR; 2 SHIFTS/DAY; 5280 HR/YR

CAPACITY - 8000 CFM @ 60°F

ITEM	DESCRIPTION	COST	
		$/YR	$/MSCF
RAW MATERIALS			
UTILITIES:			
PROCESS WATER	$ .30/10^3 GAL × 2400 GPH × 5280 HR/YR	3800	
COOLING WATER	$ .03/10^3 GAL		
STEAM	$ 1.00/10^3 LB		
NATURAL GAS	$ .60/10^6 Btu		
ELECTRICITY	$ .015/KWH × .746 $\frac{KW}{HP}$ × 110 HP × 5280 $\frac{HR}{YR}$	6480	
MAINTENANCE:			
GENERAL MAINT.	5% CAPITAL (37,200)	1860	
MAINT. SUPPLIES			
DIRECT LABOR	.5 HR/SHIFT × 660 SHIFT/YR × $ 4.00/HR	1320	
SUPERVISION	10% DIRECT LABOR	132	
DIRECT MFG. COST		13,592	
PAYROLL OVERHEAD	30% DIRECT LABOR	396	
PLANT OVERHEAD	50% DIRECT LABOR	660	
PACKING			
SHIPPING			
INDIRECT MFG. COST		1056	
DEPRECIATION	10% CAPITAL COST (37,390)	3739	
PROPERTY TAXES	1% CAPITAL COST (37,390)	374	
INSURANCE	0.5% CAPITAL COST (37,200)	186	
FIXED MAN. COST		4299	
TOTAL PLANT LEVEL COST		18,947	
CORP. OVERHEAD	3% TOTAL PLANT LEVEL COST	568	
TOTAL MFG. COST		19,515	
	SAY	19,500	.0077

MANUFACTURING ESTIMATE-REACTOR EXHAUST STUDY

CONTROL PROCESS: SCRUBBING AND ABSORPTION OF REACTOR VAPORS

PROCESS OPERATING TIME: 330 DAYS/YR; 2 SHIFTS/DAY; 5280 HR/YR

CAPACITY- 20,000 CFM @ 60°F

ITEM	DESCRIPTION	COST $/YR	 $/MSCF
RAW MATERIALS			
UTILITIES:			
PROCESS WATER	$\$ .30/10^3$ GAL × 6000 GPH × 5280 $\frac{HR}{YR}$	9,500	
COOLING WATER	$\$ .03/10^3$ GAL		
STEAM	$\$ 1.00/10^3$ LB		
NATURAL GAS	$\$ .60/10^6$ Btu		
ELECTRICITY	$\$ .015$/KWH × 275 HP × .746 $\frac{KW}{HP}$ × 5280 $\frac{HR}{YR}$	16,200	
MAINTENANCE:			
GENERAL MAINT.	5% CAPITAL (65,200)	3,260	
MAINT. SUPPLIES		–	
DIRECT LABOR	.5 HR/SHIFT × 660 SHIFT/YR × $\$$ 4.00/HR	1320	
SUPERVISION	10% DIRECT LABOR	132	
DIRECT MFG. COST		30,412	
PAYROLL OVERHEAD	30% DIRECT LABOR	396	
PLANT OVERHEAD	50% DIRECT LABOR	660	
PACKING		–	
SHIPPING		–	
INDIRECT MFG. COST		1056	
DEPRECIATION	10% CAPITAL COST (65,530)	6553	
PROPERTY TAXES	1% CAPITAL COST (65,530)	655	
INSURANCE	0.5% CAPITAL COST (65,200)	328	
FIXED MAN. COST		7536	
TOTAL PLANT LEVEL COST		39,004	
CORP. OVERHEAD	3% TOTAL PLANT LEVEL COST	1,170	
TOTAL MFG. COST		40,174	
	SAY	40,200	.0063

APPENDIX E

INCINERATION-SCRUBBING SYSTEMS
FOR
HYDROCARBON EMISSION CONTROL

ACKNOWLEDGMENTS

Appreciation is hereby expressed to the Maurice A. Knight Company for their cooperation in permitting use of their file data and design examples. In particular, the support of Mr. M.A. Knight, Jr., in allowing release for publication of the pressure drop and flooding correlations, and the help of Mr. David Cooper in reviewing the calculations is particularly appreciated. Permission of the Garver-Davis Company to use computer print-out data for petrochemical waste incineration furnace design is also duly acknowledged.

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SUMMARY

The design technology of incineration-scrubbing systems for the disposal of organic and hydrocarbon wastes under conditions avoiding the emission of secondary hydrocarbon-derived contaminants has been reviewed and evaluated. The scrubbing design techniques covered are those for sizing equipment based on a sequence of adiabatic quench of the hot combustion gases, followed by absorption of soluble gas contaminants in a cooling-dehumidification section. The design approach to each of these sections is based on separate and distinct heat transfer considerations. The absorption of soluble pollutants is a secondary and incidental design consideration, because satisfying the heat transfer requirements for quench-cooling of the hot combustion gases generally provides for the necessary dissolution of soluble gas contaminants such as partially-oxidized hydrocarbons and inorganic acid gases.

A number of hitherto-proprietary precise industrial design correlations and methods for the estimation of packed-tower scrubber flow area and pressure drop are presented for the first time. The use of these techniques is demonstrated for an industrial design case-history involving the incinerative disposal of DDT-kerosene solution, with complete removal of the HCl formed on combustion. Because certain aspects of the full design procedure are empirical and not rigorous, information has been provided on all necessary approximations and safety factors required to achieve a feasible design. This installation is in operation and meeting all design specifications, and the techniques described are equally applicable to the design of scrubbers for the control of soluble oxygen-containing hydrocarbons.

Although the area and pressure drop design methods are highly accurate and reliable, considerable uncertainty still exists regarding packed height estimation for cooling-dehumidification operations. Because countercurrent contact height is the primary factor controlling the degree of contaminant removal, and thus the level of emission, additional research work is needed in this area, and general research program recommendations are presented.

I. INTRODUCTION

The purpose of this study was to identify and present the technology involved in incineration-scrubbing systems, with emphasis on the nature of the design problems and adequacy of the data base involved in the scrubbing train-portion of the system. Incineration of industrial organic liquid sludges, and the combustion of municipal garbage and other solid wastes is a popular method of disposal, and, when due care is taken in system design to prevent air pollution problems resulting from the combustion process, is an acceptable disposal technique with regard to total emissions. However, combustion of organic wastes, particularly with the usual heterogenous feed compositions encountered, can result in secondary organic and inorganic emissions which can be serious health or material hazards. These include:

1. Possibly carcinogenic polynuclear hydrocarbons usually emitted in association with carbonaceous particulates (Hangebrauck, 1967).

2. Acid gases resulting from halogen, sulfur or nitrogen constituents of the incinerated wastes.

3. Partially-oxidized hydrocarbons such as "acids, anhydrides, lactones and unsaturates due to thermal cracking and oxidation in the combustor" (Sandomirsky, 1966).

Wet scrubbing of the combustion off-gases is fairly effective for the removal of all three classes of possible air pollutants listed, and both spray and packed tower scrubbing have been employed for combustion gas treatment. Because of certain inherent deficiencies of spray tower scrubbing for multi-stage equilibrium contacting requirements, the packed tower is generally preferred for this type of operation. In particular, packed tower technology for the case of halogen-acid removal or recovery from a combustion gas pre-dates air pollution control efforts, and "package" incinerator/packed scrubber systems have been available for some years from both incinerator and packed tower manufacturers. A schematic of this type of system is shown in Figure 1-1, which is a double-tower unit required for the complete removal of moderately-soluble acid gases such as SO_2.

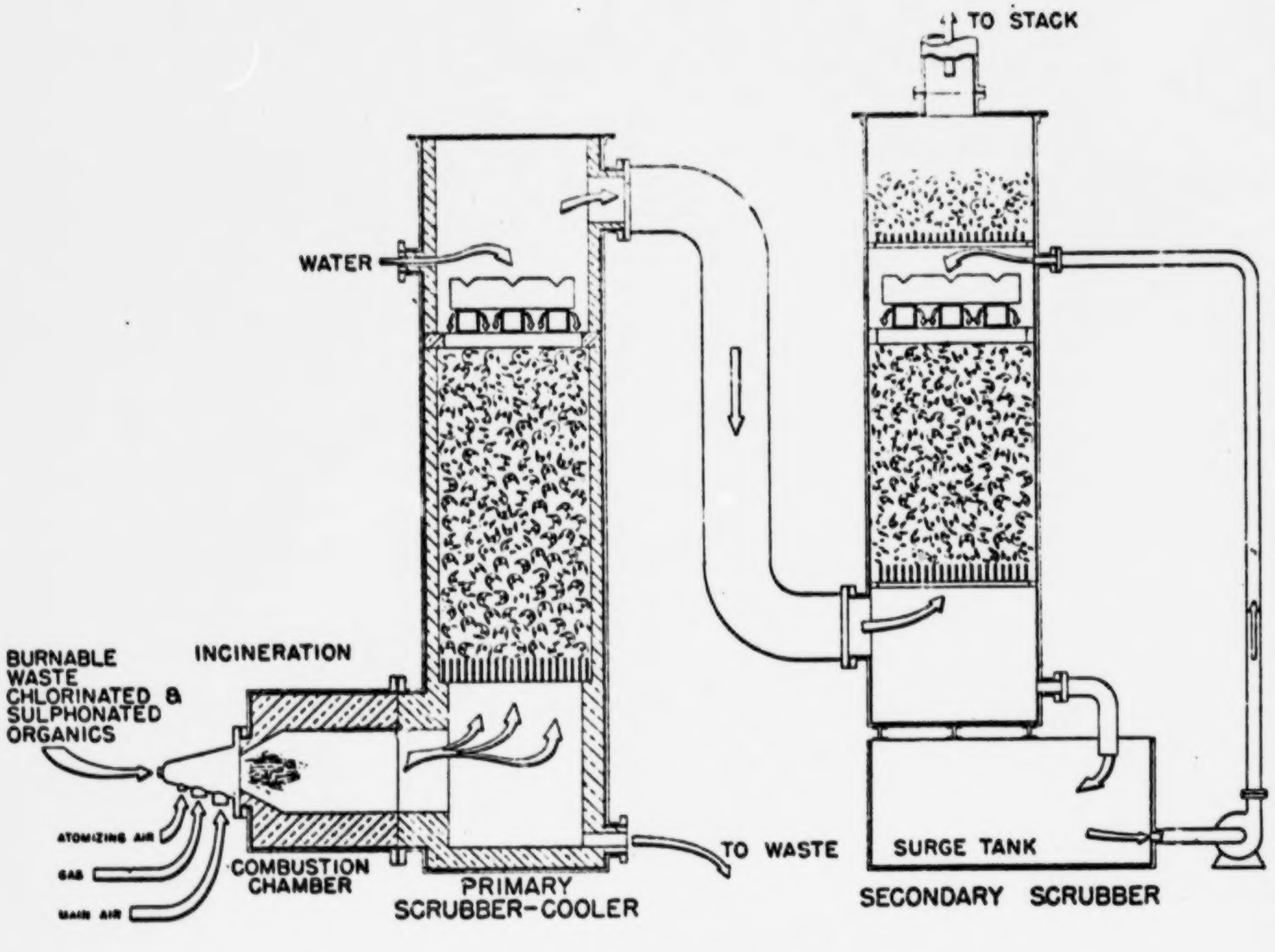
While the design of scrubber systems is normally predicated either on heat transfer or acid-gas dissolution requirements, packed and spray scrubbers also have certain capabilities for both particulate and oxidized hydrocarbon removal. The use of irrigated packed towers for direct particulate emission control has not been explored, although it has been observed in a number of industrial installations that the control level achievable is quite high. On the other hand, the extent of removal of water-soluble oxidized organic emissions in a scrubber system is directly calculable, and the design methods reviewed in this report for acid-gas removal apply equally to the oxidized hydrocarbon pollutants in the combustion gases.

As indicated in Figure 1-1, the primary tower serves as both a quench unit for the hot combustion gases, and as a scrubber for the more readily-soluble gases. For the case of chlorinated organics, or other materials which will yield a highly-soluble gas contaminant on combustion, the primary scrubber-cooling tower is all that is required for complete contaminant control. This simplified single-tower system is also highly applicable to contaminants comprised of partially-oxidized hydrocarbons because most of this class of compounds have ready solubility in water.

Because the size of such installations is usually small, and operation may be intermittent, the heat released on combustion is not utilized for steam generation. However, in several industrial installations, the waste sludge or slurry to be incinerated contains sufficient water to warrant pre-concentration by using this stream as the primary tower quench-scrub liquor prior to pumping it to the incinerator. This form of direct-contact heat utilization for waste concentration effects a measure of fuel economy by saving on the supplementary natural gas or other fuel required to sustain combustion, and it is expected that, where applicable, this operation will see increasing use.

The secondary scrubber is generally used only for difficultly-soluble gases which require chemical reaction for complete removal. The most common case is the removal of SO_2 with recycled dilute caustic solutions, where an in-

COURTESY OF
MAURICE A. KNIGHT COMPANY
AKRON, OHIO


TO STACK
WATER
BURNABLE WASTE CHLORINATED & SULPHONATED ORGANICS
INCINERATION
ATOMIZING AIR
GAS
MAIN AIR
COMBUSTION CHAMBER
PRIMARY SCRUBBER-COOLER
TO WASTE
SURGE TANK
SECONDARY SCRUBBER

LIQUID ORGANIC
WASTE DISPOSAL

itial batch of 8 to 10 wt.% NaOH is circulated until the concentration drops below 1 or 2%, at which point it is discarded. Where secondary chemical reaction scrubbing is employed, the exit gas temperature of the primary tower is controlled to allow optimum mass transfer/reaction rates in the second tower, and the entering temperature specification becomes a design element on the primary scrubber. Alternatively, where the exit gases from the primary scrubber pass directly to the stack, steam plume or buoyancy considerations govern.

Because the problems of design of an old-in-the-art pollution control device such as the packed scrubber provide an insight into the general methodology and data base adequacy of control technology, a detailed review of design procedures was undertaken. Many of the design methods covered in this review have not previously been published, but have been employed for industrial design problems for a number of years.

II. FURNACE DESIGN CONSIDERATIONS

Furnace design is a highly-specialized and standardized field, and this aspect of the incineration/scrubbing operation will not be considered in this report. However, the temperature and composition of the combustion gases are the primary working data for the design of the quench-scrubbing system, and this determination is of major importance. The industrial modus operandi is for the furnace manufacturer to supply the scrubber manufacturer the detailed composition and thermal information necessary for scrubber design calculations. The separation of the areas of technical expertise between furnace and scrubber manufacturers requires the preliminary initiation of a high level of liaison and data exchange in order to arrive at the optimum overall design, and joint design responsibility is the rule.

Prior to the advent of the electronic computer, the estimation of combustion gas temperature and compositions was a tedious task of approximation. The computer, and the availability of reliable chemical reaction equilibria data from various rocket development programs, has simplified the problem of composition determination, and has provided much more precise information. A typical computer program is that provided by the Lewis Research Center of NASA, available (without charge) as the Lewis CEC, or Chemical Equilibrium Calculation program. This is the program used by one furnace manufacturer, Garver-Davis, Inc., and they have provided the computer printout data of Table 2-1, taken from a typical industrial problem requiring the incineration of a waste chlorinated hydrocarbon stream. While compositional equilibria are stated at several temperature levels, the true operating temperature is a function of the firing rate, and this quantity is specified by the furnace engineers.

It should be noted that the furnace and primary quench scrubber are most often built as an integral, compact assembly. This is the result of the fact that ceramic materials are common to the furnace firebrick and the acid-brick lining of the scrubber and the extended-surface packing it contains. Figure 2-1 is a photo of such an installation with the furnace in the foreground and the scrubber in the rear. This installation is the one for which the detailed design example is presented below in Section IV.

```
                                  GARVER-DAVIS, INC.
                                POLLUTION CONTROL SYSTEMS


                     INCINERATOR COMBUSTION PRODUCTS ANALYSIS PREPARED FOR

                                        [redacted]
                                     LAKE CHARLES, LA.

                                       SECOND STREAM


                        THERMODYNAMIC EQUILIBRIUM PROPERTIES AT ASSIGNED
                                 TEMPERATURES AND PRESSURES


                                                                      WT FRACTION
           CHEMICAL FORMULA                                            (SEE NOTE)
WASTE   C  2.00000   H  2.00000   CL 2.00000                              .26042
WASTE   C  2.00000   H  1.00000   CL 3.00000                              .41667
WASTE   C  2.00000   CL 6.00000                                           .03125
WASTE   C  5.00000   H 10.00000   CL 2.00000                              .05208
WASTE   C  3.75000   H  5.00000   CL 1.41000                              .23958

OXIDANT O   .21000   N   .79000                                          1.00000


COMBUSTION CONDITIONS


FUEL TO WASTE WEIGHT RATIO=   .00000

OXIDANT TO WASTE WEIGHT RATIO=  4.07726

PERCENT EXCESS AIR=  20.0000

P, ATM             1.000    1.000    1.000    1.000    1.000
T, DEG F            1200     1400     1600     1800     2000

MOLE FRACTIONS IN INCINERATOR COMBUSTION PRODUCTS


CO2              .141987  .141578  .141288  .141072  .140895
CL               .000016  .000078  .000268  .000728  .001643
CLO              .000000  .000001  .000002  .000005  .000009
CL2              .020158  .014378  .010340  .007497  .005444







HCL              .082907  .094050  .101682  .106719  .109752
H2O              .033910  .028122  .024151  .021518  .019906
NO               .000005  .000017  .000050  .000117  .000240
N2               .695169  .693163  .691725  .690634  .689708
OH               .000000  .000000  .000000  .000002  .000006
O2               .025848  .028612  .030493  .031708  .032396

ADDITIONAL PRODUCTS WHICH WERE CONSIDERED BUT WHOSE MOLE FRACTIONS WERE LESS THAN .000005 FOR ALL ASSIGNED CONDITIONS

C          C(S)       CCL        CCL2       CCL3       CCL4       CH         CH2        CH3        CH4
CN         CN2        CO         COCL       COCL2      C2         C2H        C2H2       C2H4       C2N
C2N2       C2O        C3         CLCN       CLO2       CL2O       H          HCN        HCO        HO2
H2         H2O(L)     H2O(S)     N          NH         NH2        NH3        NOCL       NO2        NO2CL
N2C        N2H4       N2O        N2O4       O

NOTE, WEIGHT FRACTION OF WASTE IN TOTAL WASTE, OF FUEL IN TOTAL FUEL, AND OF OXIDANT IN TOTAL OXIDANT.
```

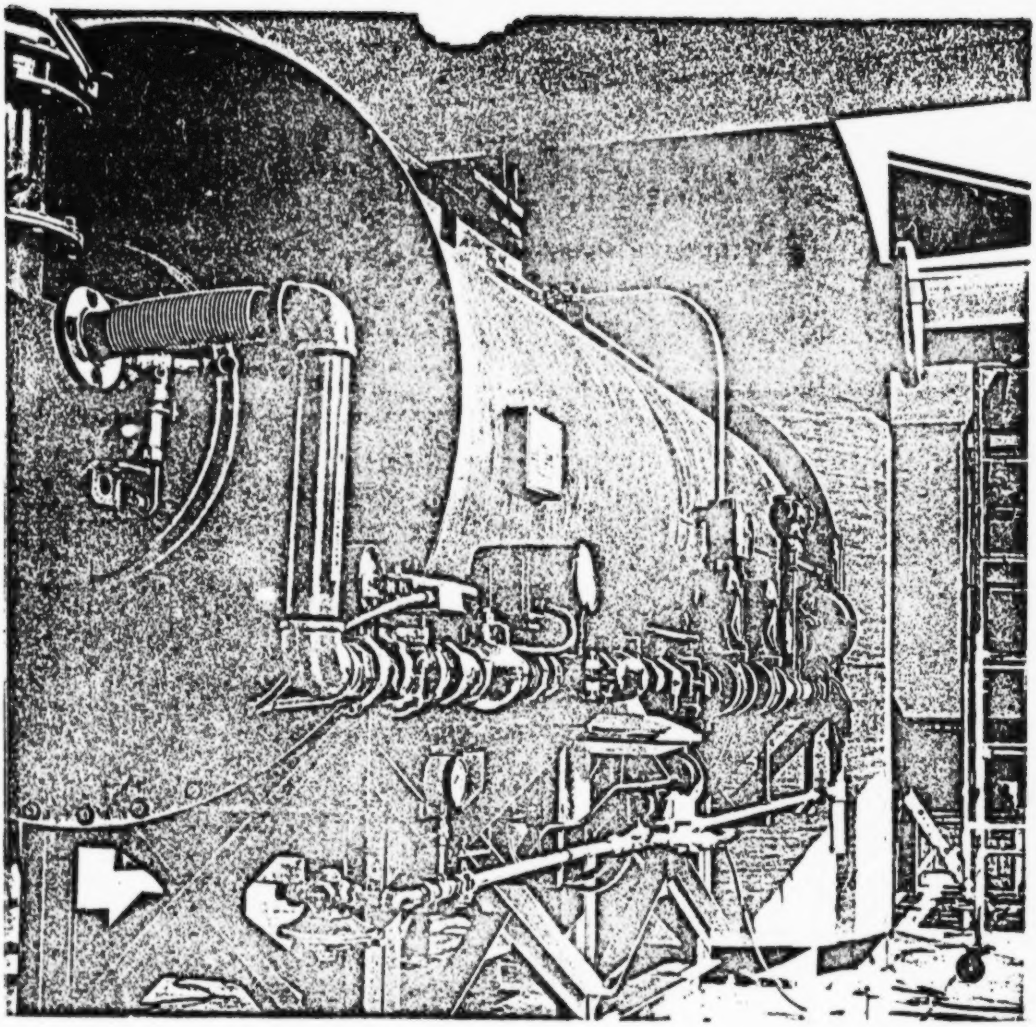


FIGURE 2-1

PHOTO OF INCINERATOR-SCRUBBER
INSTALLATION OF SECTION V CASE-HISTORY

III. ABSORPTION TRAIN DESIGN

The standard design approach to sizing the packed tower absorption train on an organic waste incineration process consists of four procedures:

1. Weight Flow Calculation: The liquid flows required for treating the given amount of combustion gases are calculated from heat and mass balances.

2. Tower Area Estimation: Tower cross-sectional flow areas are estimated from limiting flow (flooding) equations and pressure drop considerations for the calculated weight flow rates of gas and liquid for several packing sizes. The ultimate choice however is an economic one.

3. Packing and Tower Height Estimation: Packing depths are calculated for the specified degree of heat or contaminant removal from literature or experimental data on transfer efficiency of a unit height of packing, or volumetric capacity coefficients, if and when available.

4. Pressure Drop Calculations: Pressure drop through the absorption train is estimated from available correlations using the mass liquid and gas flow rates and the result is either matched against, or specified for, the heat output of the combustion air blower.

The only unconventional part of the absorption-train design procedure concerns the first tower. The direct-contact quenching-cooling functions of the first tower are primary, and this tower is therefore designed on a heat transfer basis. In situations where a highly-soluble acid-gas such as HCl is the major contaminant specified for removal, a single-tower train is usually sufficient, because enough cooling water can be fed to the tower to serve both heat and mass transfer functions, with only nominal flow area requirements. Thus, for chlorinated hydrocarbon disposal, quench-cooling tower design is the complete system design, and the general procedures for this unit are reviewed below.

A. QUENCH TOWER WEIGHT FLOW CALCULATION

The quench-cooling tower in an incineration/absorber train performs the following functions:

1. Quenching the hot combustion gases to the adiabatic saturation temperature by the evaporation of water.
2. Cooling the gas from the adiabatic saturation temperature to the desired stack temperature.
3. Completely absorbing the highly-soluble gas contaminants, and partially absorbing the moderately-soluble contaminants.

These are independent functions, and the water flow requirements for each may be separately calculated.

1. Adiabatic Saturation

In order to estimate the quench water requirement necessary for cooling the hot combustion gases to the adiabatic saturation temperature, t_{as}, the water content of the quenched gases at this temperature must be determined. Because adiabatic saturation is isenthalpic, the value of t_{as} is obtainable from the enthalpy content of the combustion gases in conjunction with an appropriate psychrometric table or chart. The enthalpy of the combustion gas is given by the experimental gross heating value of the waste, if available, or from the temperature composition data of the equilibrium furnace calculations (computer print-out). The enthalpy value per pound of dry inert combustion gas is referred to a standard air-water psychometric table, to obtain the water content at saturation. It may be assumed that the difference in molecular weight between the combustion gas and air will have a negligible effect on the quench water rate so calculated. The minimum evaporation water required, W_q, is then calculated by:

$$W_q = W_g(H_{as} - H_i) \qquad (3\text{-}1)$$

where W_g = weight rate of dry gas flow, lb/hr.

H_{as} = saturation humidity at t_{as}, lb H_2O/ lb dry gas

H_i = initial combustion gas humidity, lb H_2O/lb dry gas

2. Cooling-Condensing

If only the water of vaporization necessary to quench the combustion gases isenthalpically to the adiabatic saturation temperature were to be supplied to the quench tower, the bottom section would obviously run dry, and the tower would have no capability for sorption. It is therefore necessary to supply water to the first tower in excess of the adiabatic evaporation needs in order for it to function as a scrubber. There are several possible methods of calculating the total water requirements of the quench tower, including:

(a) Total Liquid Heat Load: The water rate is determined by the maximum allowable exit liquor temperature, under the total liquid heat load and maximum inlet water temperature. Total liquid heat load is calculated as the sum of the gas enthalpy change over the tower plus the heat of absorption and dilution of dissolved solubles.

(b) Minimum Sorption Liquid: The outlet liquid temperature and HCl concentration is determined by trial-and-error for the two constraints of an inlet gas HCl concentration greater than the equilibrium back-pressure of HCl over the exit solution, and a total enthalpy balance around the tower.

(c) Steam Plume Considerations: Depending on the climate and local conditions, it may be necessary to limit the exit gas temperature to minimize steam plume formation. If ample quantities of cold water are locally available, the steam plume may be suppressed by using the tower feed water to cool and dehumidify the gas by direct-contact cooling and condensation (Kalika, 1969).

For the single-tower absorption case, the mass transfer requirement of (b) is almost always satisfied by the amount of water needed for the secondary cooling following the quench as calculated from an enthalpy balance. It is then only necessary to check that the partial pressure of the soluble contaminant in the exit liquor, at exit temperatures is less than the partial pressure of the contaminant in the entering combustion gas. This avoids trial-and-error mass transfer calculations, and also places the primary emphasis on the thermal considerations, which control the design.

B. TOWER AREA

The design value for the cross-sectional area of a packed tower is estimated from the limiting capacity or flooding velocity of the packing. While "generalized" correlations for flooding velocities are available, these are stated in terms of arbitrary "packing factors" and their use does not permit "tight" design, and frequently leads to serious error (Prahl, 1970). In addition, the generalized flooding and pressure drop correlations contain no correction for such significant physical system parameters as liquid surface tension, or greatly distort the effect of variables such as liquid density. Because of these and other limitations, alternate and more precise estimating methods have necessarily been developed and employed. It should be noted that rigorous design convention calls for setting the operating mass gas flow rate at 70% of the limiting flood gas rate for the established liquid mass flow. Uncertainty in estimating the limiting gas flow rate can be covered by dropping the design basis to 40-50% of estimated flood, but this is a poor design approach which results in an unnecessarily larger and more expensive tower. The 70% flood design will generally result in operation slightly in excess of the load point, which is the most efficient region of operation with respect to mass transfer.

Use of the 70% flood limit as a basis for tower design requires a precise mathematical statement of this limit, and specific packing equations: theoretically based and experimentally-verified, were developed by Lerner (1951) and later independently confirmed by Howkins (1958). The flooding equations are of the form:

$$(G_o/\phi)_F = k(1 - mL_o^{0.57})(\sigma/\sigma_w)^n \qquad (3\text{-}2)$$

where G_o = gas mass flow rate, lb/hr/ft^2

L_o = liquid mass flow rate, lb/hr/ft^2

ϕ = gas density correction factor = $(\rho_g/0.075)^{0.5}$

ρ_g = gas density, lb/CF

σ_w = surface tension of water

k,m,n = constants

The constants, k and m, are specific for each packing type, and size, and values of these constants are presented in Table 3-1. These constants have been evaluated from the data of Lubin (1949), one of the few independent studies of packed tower limiting flows. As indicated in Table 3-1, for most packings there is an apparent change in flow mechanism at a certain high critical liquid flow rate, which is specific for the packing. Accordingly, it is found that two equations, involving a low-range and high-range set of constants, yield a better fit to the data than one overall equation. The nature of this critical transition liquid rate is examined in more detail in Section 3-4.

The estimation of tower area from the flooding equations of Table 3-1 involves a limited amount of trial-and-error calculation. Although the initial value for tower area for a given packing must be assumed, the use of the 70% flood design base and the appropriate flooding equation yields very rapid convergence on the correct design area for the second or third trial. The estimation procedure based on the equations of Table 3-1 have therefore proved amenable to programming for automatic calculation for the simple desk-top electronic calculators. A magnetic card program for area estimation based on the flood equations of Table 3-1 is available from the Hewlett-Packard Company Program Library for use on their 9100-B calculator. The hand-calculations required without electronic-calculator help for a single design are not extensive, and can be outlined as follows:

(a) Choose a packing and assume a flow area, A_1

(b) From the given weight rate of liquid and gas flows, calculate the mass flows, $(L_o)_1$ and $(G_o)_1$, and G_o/ϕ) for the assumed A_1.

TABLE 3-1

CONSTANTS FOR FLOODING VELOCITY EQUATION

$$(G_o/\emptyset)_F = k(1 - m\, L_o^{0.57})\, (\sigma/\sigma_w)^n$$

$$n = 0.58 \text{ for low range } (L_o/\rho_L)$$

$$n = 1.0 \text{ for high range } (L_o/\rho_L)$$

Packing Type and Size	(L_o/ρ_L) Range	k	m x 10^2
Ceramic Raschig Rings			
3/4"	Low: $<$ 136.5	1685	3.53
	High: $>$ 136.5	1518	3.28
1"	Low: $<$ 144.5	1870	3.65
	High: $>$ 144.5	1420	2.81
1-1/2"	Low: $<$ 209	2118	2.72
	High: $>$ 209	1500	1.88
2"	Low: $<$ 240	2280	2.33
	High: $>$ 240	2060	2.28
Ceramic Berl Saddles			
3/4"	Low: $<$ 160	1825	3.17
	High: $>$ 160	1405	2.70
1"	Overall	2360	2.64
1-1/2"	Low: $<$ 285	2740	2.13
	High: $>$ 285	---	---
2"	Low: $<$ 300	3110	1.866
	High: $>$ 300	2715	1.532

(c) Calculate $(G_0/\phi)_F$ corresponding to $(L_0)_1$ from the flood equation.

(d) Calculate the ratio, $R = (G_0/\phi)1/[(G_0/\phi)_F]_1$

(e) Assume $A_2 = (R/0.7)(A_1)$ and repeat steps (b) through (e) until $R = 0.7$.

This procedure is perhaps best illustrated by an example.

1. Example Problem in Area Estimation

In a certain paper-coating plant, toluene is used as the coating-resin solvent. Following the roll-coating operation, the solvent is removed by passage of the paper web over heated rolls, and a hood serves to remove the toluene and hot air. The exhaust gases from the blower serving the hood had previously been passed directly to the stack at 130°F at a rate of 35,000 lb/hr of solvent-free air. It is now proposed to prevent this emission by scrubbing in a packed tower with a chilled (40°F) high molecular weight hydrocarbon solvent with a specific gravity of 0.85 and a surface tension of 32 dynes/cm. The solvent-rich scrubbing oil is to be stripped in a separate column with direct steam, but the amount of surplus plant steam limits the oil circulation rate to 1700 GPM. What diameter absorption column would be required for use with 1-1/2-inch ceramic Raschig rings?

Trial 1: Assume $A_1 = 100\ \text{ft}^2$

$$L_0 = \frac{(1700)(8.34)(0.85)(60)}{(100)} = 7{,}200\ \text{lb/hr/ft}^2$$

$$(L_0/\rho_L) = 135.8$$

From Table 3-1, $(L_0/\rho_L)_c = 209$, and low-range equations apply.

$$(G_0/\phi)_F = 2118[1-0.0272(L_0/\rho_L)^{0.57}](\sigma/\sigma_w)^n$$

ϕ: assume tower exit gas t = 60°F.

$$\text{Average Gas Temperature} = \left(\frac{130 + 60}{2}\right) = 95°\text{F}.$$

$$\rho_G = (29/359)(492/555) = 0.0716\ \text{lb/CF}$$

$$\phi = (0.0716/0.075)^{0.5}$$

$$\phi = 0.978$$

$$(\sigma/\sigma_W)^n = (32/73)^{0.58}$$

$$= 0.621$$

Now:

$$(G_o)_F = (0.978)(2118)[1 - 0.0272(135.8)^{0.57}](0.621)$$

$$= (0.978)(2118)(0.553)(0.621)$$

$$= 711 \text{ lb/hr/ft}^2$$

$$(G_o)_{act} = 35{,}000/100 = 350 \text{ lb/hr/ft}^2$$

$$(G_o)_{act}/(G_o)_F = (350/711) = 49.3\%$$

Trial 2: $A_2 = (0.493/0.700)(100) = 70.4 \text{ ft}^2$

$$L_o = (7{,}200/0.704) = 10{,}230 \text{ lb/hr/ft}^2$$

$$(L_o/\rho_L) = (135.8/0.704) = 193$$

$$(G_o)_F = (0.978)(2118)[1 - 0.0272(193)^{0.57}](0.621)$$

$$= (0.978)(2118)(0.436)(0.621)$$

$$= 561 \text{ lb/hr/ft}^2$$

$$(G_o)_{act} = 35{,}000/70.4 = 498 \text{ lb/hr/ft}^2$$

$$(G_o)_{act}/(G_o)_F = (498/561)(100) = 88.7\%$$

Trial 3: $A_3 = (0.887/0.70)(70.4) = 89.2 \text{ ft}^2$

$$(L_o/\rho_L) = (193)(70.4/89.2) = 153.3$$

$$(G_o)_F = (0.978)(2118)[1 - 0.272(153.3)^{0.57}](0.612)$$

$$= (0.978)(2118)(0.537)(0.621)$$

$$= 691 \text{ lb/hr/ft}^2$$

$$(G_o)_{act} = (35{,}000/89.2) = 392 \text{ lb/hr/ft}^2$$

$(G_o)_{act}/(G_o)_F = (392/691)(100) = 56.8\%$

Trial 4: Take $A_4 = \frac{A_2 + A_3}{2} = \frac{70.4 + 89.2}{2} = 79.8\ ft^2$

$(L_o/\rho_L) = (135.8/0.798) = 170$

$(G_o)_F = (0.978)(2118)[1 - 0.0272\ (170)^{0.57}](0.621)$

$= (0.978)(2118)(0.491)(0.621)$

$= 632\ lb/hr/ft^2$

$(G_o)_{act} = (35{,}000/79.8) = 439\ lb/hr/ft^2$

$(G_o)_{act}/(G_o)_F = (439/632)(100) = 69.4\%$

Tower Diameter: $D_o = [(4/\pi)(79.8)]^{0.5}$

$= (101.7)^{0.5}$

$= 10'\text{-}0''$

Choice of a proper packing and packing size is a matter of some engineering judgment and experience, but the above procedure will quickly reveal any flow-capacity inadequacy if the wrong choice is made. In actual practice, as will be discussed below, the packing choice is also governed by pressure drop limitations, and it is necessary to cross-check the design mass flows for the head requirements once the packed height requirement is known. It should be mentioned here that the calculator program containing the mathematical statement of the flood (and load) curves, also contains mathematical equations giving the complete pressure-drop vs. flow behavior for each of the packings of Table 3-1.

C. PACKED HEIGHT COMPUTATION

The packed height requirement for the quench tower is normally estimated as the sum of the two separate depths corresponding to the two distinct and consecutive functions of adiabatic saturation at the gas inlet section, and cooling-condensing in the upper section. Alternate approaches are possible, but these generally involve simplifying assumptions as to the adiabatic saturation section requirements and location. Despite pre-packing contact, it is good practice to assume quenching does not occur until the gas enters the packing. Although the following treatment is not rigorous, it comprises a conservative design procedure, utilizing the best current information on transfer coefficients.

1. Adiabatic Saturation

While the literature contains a number of studies of heat transfer coefficients for the adiabatic saturation of air with water, these have been determined only for a very narrow choice of packings and low-temperature conditions. Further, the absolute heat and mass transfer coefficient values reported are not always corrected for packing end-effects, which are relatively large for the shallow packed depths necessarily employed to avoid equilibrium saturation under laboratory conditions. For example, Hensel and Treybal (1952) reported extensive data for 1-1/2" Berl saddles, and when the data were extrapolated to infinite tower height, the heat transfer coefficients underwent a three-fold reduction from the observed shallow-bed values. Thus, certain manufacturer's test data on shallow beds should not be used without correction for the relatively large and variable end-effects. There also appears to be a high degree of disparity between field experience on gas-liquid contact time and area requirements for the equilibrium quenching of hot combustion gases, and the highly optimistic laboratory results on low-temperature transfer coefficients given in the literature. For example, for spray chamber quench units employing recirculated water, design practice (Kalika, 1969) calls for only 60% evaporation of the liquid injected into the gas. For packed towers it has been found that a heat-transfer (HTU)(NTU) approach yields comparatively conservative contact depth estimates and by conversion, allows the use of the extensive literature (HTU) values for mass transfer.

(a) Height of Transfer Unit for Heat Transfer:

The correlation that allows conversion of the literature values for mass transfer, $(H_G)_d$, to the heat transfer values of $(H_G)_h$, is that of Wilke et al (1963), which is stated for the case of gas-film resistance controlling as:

$$(H_G)_h = (H_G)_d (D/\alpha)^{0.5} (\mu_d/\mu_h)^{0.27} (\rho_h/\rho_d)^{0.84} (\sigma_h/\sigma_d)^{0.925 - 0.262 \log(L)} \qquad (3\text{-}3)$$

Where: D_G = mass diffusivity, sq ft/hr

α = thermal diffusivity, sq ft/hr

L = mass liquid flow rate, $lb/hr/ft^2$

ρ = gas density

σ = liquid surface tension

μ = gas viscosity

h,d = subscripts denoting heat and mass transfer, respectively.

The group, (D_G/α) in Equation (3-2) is somewhat difficult to evaluate as written, because direct data on thermal diffusivities are not readily available. However, by definition: $\alpha = (k/\rho C_p)$ (3-4)

Where: k = thermal conductivity

C_p = heat capacity

and the group, $(D_G/\alpha) = (C_p\mu/k)/(\mu/\rho D_G) = (Pr)/(Sc)$ (3-5)

Where: Pr = Prandtl Number, $(C_p\mu/k)$

Sc = Schmidt Number, $(\mu/\rho D_G)$

Because the moles of water/mole dry gas at the adiabatic saturation temperature, t_{as}, conditions prevailing in the gas film adjacent to the liquid is generally greater than 2/1, the Prandtl number for steam is more truly descriptive of thermal transport than that for air.

The value of $(H_G)_d$ in the Equation (3-2) may be evaluated from the data of Fellinger (Sherwood and Pigford, 1952) for the ammonia-air-water system, and converted to the water-air-water system by the relationship:

$$(H_G)_{H_2O} = (H_G)_{NH_3} (Sc_{H_2O}/Sc_{NH_3})^{0.5} \qquad (3\text{-}6)$$

or

$$(H_G)_{H_2O} = (H_G)_{NH_3} (D_{NH_3}/D_{H_2O})^{0.5} \qquad (3\text{-}7)$$

Inasmuch as the diffusivities and Schmidt numbers for water and ammonia are virtually identical, with Sc_{H_2O} = 0.60, and Sc_{NH_3} = 0.61, the $(H_G)_{NH_3}$ values for the reference NH_3-air-water system can be used directly for $(H_G)_{H_2O}$ with less than 2% error.

(b) Number of Transfer Units:

The number of transfer units for heat transfer based on gas-film resistance controlling $(N_G)_h$, may be stated as:

$$(N_G)_h = \frac{t_2 - t_1}{(\Delta t)_m} \qquad (3\text{-}8)$$

$$= 1 \frac{haZ}{C_pG} \qquad (3\text{-}9)$$

where t_1, t_2 = leaving and entering gas temperatures, respectively

$(\Delta t)_m$ = log mean temperature driving force

ha = gas film volumetric heat transfer coefficient, Btu/hr/ft³/°F

Z = packed height, ft

G = mass gas flow, lb/hr/ft²

In order to assess the relative magnitude of the adiabatic cooling NTU requirements, if it is assumed that a hot combustion gas must be cooled from 1800°F, to an adiabatic saturation temperature of 180°F, using water at 140°F (assumed constant) the transfer unit requirements are then calculated to be:

$$(N_G)_h = \ln(1660/40) = 3.73$$

For stagewise contacting, assuming that (approximately)NTU = NTP, the requirement for close to four equilibrium stages indicates that, despite what may appear to be a large driving force, the multi-stage requirements are significant. For the case of the spray chamber, relative gas-liquid velocities vary and are unstable, and departure from true countercurrent flow can be caused by gas reciruclation due to liquid jet momentum. Thus, for the example shown, if the true evaporation efficiency value of Kalika (1969) mentioned previously is used, then a total of seven spray stages would be required to satisfy the indicated NTU. On the other hand, for a packed tower, with true differential countercurrent contact, assuming a representative order-of-magnitude value for $(H_G)_h$ of 1 foot, the same transfer can be effected in less than four feet of packed depth. Thus, as has been shown by Pigford and Pyle (1951), where conditions allow the use of the packed tower, this is a more effective contacting unit than a spray chamber.

2. Cooling-Condensing

Following passage through the evaporative cooling section at the bottom of the tower, the gas then flows through the upper section where, if the feed water is below the adiabatic saturation temperature, the gas is cooled and part of the water evaporated in the bottom section is condensed. Unlike the adiabatic evaporation process, which is unequivocally gas-film controlled, the cooling-condensing section involves liquid-phase resistance to heat transfer. The degree of this additional resistance, and its effect on design assumptions, has been the subject of a great deal of dispute but little clarification. Further, the chances for fog formation in this section are extremely good, and there is no method for handling calculations under these conditions.

Packed height estimation for the cooling-condensing region is a highly uncertain procedure, primarily because of the lack of performance data. The reasons for this lack were specifically noted and discussed by Treybal (1955) but no remedial action has been taken in the 16-year interim. It is known that a certain amount of proprietary performance information is on file and is utilized for design purposes by tower fabricating companies, but the reliability of this data is not known. The available published heat and mass transfer coefficients give inconsistent results, with height values varying from impractically-shallow beds of less than 6 inches depth, to heights in excess of 20 feet for a given problem, depending on which coefficient data and procedure is used. It would be highly desirable to have a set of HTU values for several packings, determined simultaneously on the basis of enthalpy-potential, temperature, and humidity driving forces, for the dehumidification of air by cold water. In the absence of such data, the method that has been found to give the most rational results for height estimates in this cooling-dehumidification region is to assume that the liquid film resistance controls. On this assumption, the NTU is given by:

$$(N_L)_h = \frac{(t_2 - t_1)}{(T_2 - t_2) - (T_1 - t_1)} \quad \frac{(t_2 - t_2)}{(T_1 - t_1)} \quad (3\text{-}10)$$

where

T = gas temperature

t = water temperature

1,2 = subscripts denoting top and bottom of packed section, respectively

As was the case for the gas-film coefficients, the liquid-film coefficients are obtained by use of the equations of Wilke, et al (1963) for converting $(H_L)_d$ literature data on the desorption of oxygen from water to the corresponding heat transfer value, $(H_L)_h$:

$$(H_L)_h = (H_L)_d (D/\alpha)^{0.5} (\mu_h/\mu_d)^{0.55} (\rho_d/\rho_h)^{0.329} (\sigma_d/\sigma_h)^{0.554-0.157 \log(L)} \quad (3\text{-}11)$$

Because of the fairly large uncertainties in the use of liquid-film coefficients in the absence of direct supporting data, it is necessary to use adequate safety factors. It is usual practice to use a 1.5 multiple (50% safety factor) of the total theoretical packed height of both quenching and dehumidification sections to cover the inadequacies in the basic coefficient data.

D. PRESSURE DROP COMPUTATION

Estimation of the flow resistance of the scrubbing train is necessary in order to specify the heat requirements for the combustion air blower on the furnace. As shown in Figure 3-1, the pressure drop through a packed tower consists of several losses in addition to the "intrinsic" pressure drop through the packing itself. However, while these secondary head losses cannot be neglected, for packing depths of more than a few feet, the intrinsic pressure loss of the packing itself is the major item in the head requirement inventory.

Although partial correlation of packed tower pressure drop was achieved a number of years ago (Treybal, 1955) these early efforts failed to cover the higher liquid rate range where the slopes of the pre-load log-log plots of ΔP vs. mass gas velocity increased above the normal value of 1.8. The M.A. Knight Company has accomplished a complete correlation of the full pressure drop behavior of packings on the basis of defining this latter critical liquid velocity (termed the "gas-sweep" velocity) as a demarcation line which horizontally divides the ΔP vs. G_0 family of curves into two zones of operation: pre-critical and super-critical. The flooding line on the log-log ΔP plot sets the upper limit to the curves, while the loading line, which can be described mathematically in a manner similar to the flooding equations of Table 3-1, serves to vertically delineate the graphs into pre-loading and load-to-flood zones of operation. There are thus four distinct zones of pressure drop dependency on flow rates in a packed tower, and a mathematical description of the pressure drop behavior specific to each zone is derivable from analysis of the two-phase flow mechanics characteristic of each flow zone. The flow zones and generalized specific ΔP expressions are:

1. Pre-Load, Pre-Critical

$$(\Delta P/Z) = a_1(G_0/\phi)^{1.8}$$

2. Pre-Load, Super-Critical

$$(\Delta P/Z) = a_2(G_0/\phi)^{1.8} + K_1$$

3. Load-to-Flood, Pre-Critical

$$(\Delta P/Z) = a_3(G_0/\phi)^{3.0}$$

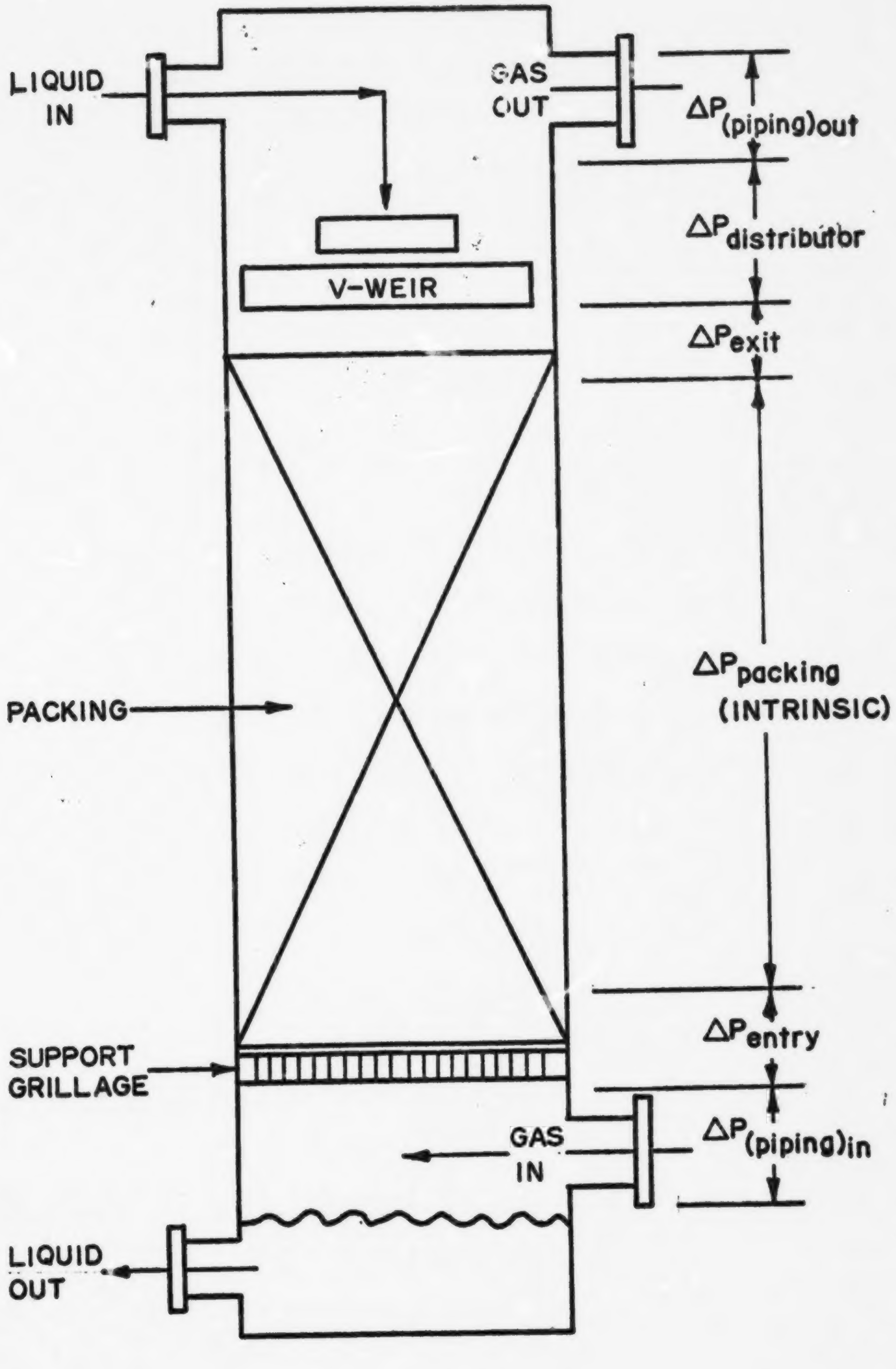

LIQUID IN
GAS OUT
$\Delta P_{(piping)out}$
$\Delta P_{distributor}$
V-WEIR
ΔP_{exit}
PACKING
$\Delta P_{packing}$ (INTRINSIC)
ΔP_{entry}
SUPPORT GRILLAGE
GAS IN
$\Delta P_{(piping)in}$
LIQUID OUT

FIGURE 3-1

COMPONENTS OF PACKED TOWER PRESSURE DROP

4. Load-to-Flood, Super-Critical

$$(\Delta P/Z) = a_4(G_o/\phi)^{3.0} + K_2$$

The fundamental utility and elegance of this correlation approach is that all of the zonal constants, a and K are functions of liquid mass flow rates and packing type and size, and the relationships may be theoretically explained. The intrinsic ΔP equations for Raschig rings and Berl saddles are presented in the Appendix to this report. The use of these equations is best illustrated by an example.

1. Pressure Drop Estimation Example

For the example tower area design problem given in Section B-1, the mass flows for 1-1/2" Raschig rings in a 10'-0" diameter tower are:

$$G_o = (439)(79.8/78.5) = 446 \text{ lb/hr/ft}^2$$

$$(L_o/\rho L) = (170)(79.8/78.5) = 172.8$$

$(L_o/\rho L)_c = 209$, L_o is pre-critical

From Table A-3, Appendix:

Loading: $(G_o/\phi)_L = 1070[1-2.14 \times 10^{-2}(L_o/\rho_L)^{0.62}]$

$$(G_o)_L = (0.978)(1070)(0.477)$$

$$= 499 \text{ lb/hr/ft}^2$$

$(G_o)_{act}/(G_o)_c = (466/499)(100) = 89.4\%$ of load

so $(G_o)_{act}$ is pre-load

From Table A-3:

Zone 1: Pre-Load, Pre-Critical Equation applies:

$$(\Delta P/Z) = a_1(G_o/\phi)^{1.8}$$

where $a_1 = 1.45 \times 10^{-6}(10^{2.60} \times 10^{-3}(L_o/\rho_L)$

and for $(L_o/\rho_L) = 172.8$,

$$a_1 = (1.45 \times 10^{-6})(2.83)$$

$$= 4.10 \times 10^{-6}$$

$$(\Delta P/Z) = (4.10 \times 10^{-6})(6.11 \times 10^{4})$$

$$= 0.25\text{" } H_2O\text{/ft of packing}$$

IV. DESIGN CASE HISTORY

CASE HISTORY NO. 1

The client's disposal problem involved the incineration of 100 gallons/hour of 5% by weight DDT solution in kerosene. The gross heating value of the solution was experimentally determined as 20,700 Btu/lb, and the density of the mixture as 50 lb/ft³. Removal of the HCl formed on combustion is desired, and cold, fresh water is readily available at the plant site, with a maximum summer temperature of 50°F. The allowable maximum waste water temperature is 175°F.

1. Material Balance

Basis: 1 Hour

$$\text{Total Weight Liquid Burned} = \frac{(100\ \text{gal/hr})(50\ \text{lb/CF})}{(7.48\ \text{gal/CF})}$$

$$= 668\ \text{lb/hr}$$

Composition	wt %	lb/hr	M. wt	Mole/hr	Cl lb atom/hr
DDT: $C_{14}H_9Cl_5$	5	33.4	354.5	0.0944	0.04720
Kerosene: $C_{0.85}H_{0.15}$	95	634.6	10.35	61.3	
		668.0		61.3944	

2. Flue Gas Analysis and Flow Rates

The combustion gas analysis was obtained directly from the computer program on thermodynamic equilibrium for the furnace combustion products (Lewis, NASA CEC Program). For this case, at a temperature of 1600°F, the following flue gas composition was calculated.

Component	Mole %	Mole/hr.	lb./hr.
CO_2	16.5948	54.2	2385
N_2	78.2904	254.5	7120
O_2	3.4679	11.3	362
NO	0.0131	0.0427	1.2
OH^-	0.0001	---	---
Cl_2	0.0012	---	---
(Inert)	98.3675	320.678	9868.2
HCl	0.1448	0.4720	17.22
Total (Dry)	98.5123	321.15 (BDG)*	9885.42
H_2O	1.4874	4.85	87.3
Total (Wet)	99.9997	326.0	9972.7

*Bone Dry Gas

3. Adiabatic Saturation Temperature

The value of t_{as} is determined as that corresponding to the gas enthalpy content.

Heat Release = (20,700 Btu/lb.)(668 lb./hr.)

= 13,800,000 Btu/hr.

$$\text{Enthalpy Content} = \frac{13,800,000 \text{ Btu/hr.}}{9885.42 \text{ lb./hr. BDG}}$$

= 1397 Btu/lb. BDG

From psychrometric table in Perry (1963) p. 15-7, by interpolation:

t_{as} = adiabatic saturation temperature = 191.2°F.

water content at t_{as} = 1.184 lb. H_2O/lb. BDG

saturated volume at t_{as} = 47.27 $ft.^3$/lb. BDG

4. Adiabatic Saturation Water Requirement

lbs. Water Evaporated/hr. = (1.184)(9868.2) - 87.3

= 11,690 lb./hr.

5. Feed Water Rate (Total)

Based on steam-plume considerations (see Kalika (1969) and Crocker (1968)) and local meteorological conditions at the plant site, the exit saturated gas temperature from the tower will be limited to 130°F. maximum.

At 130°F., Saturated

Gas Enthalpy = 155.9 Btu/lb. BDG

Water Content = 0.116 lb. H_2O/lb. BDG

Gas Volume = 17.516 CF/lb. BDG

Overall Net Tower Heat Load

(a) Dry Gas = 13,800,000 - (155.9)(9868)

= 12,262,000 Btu/hr.

(b) HCl: Heat generated by absorption (Perry, 1963, p. 3-137)

Ht. Formation HCl (aq.) = -39.85 kcal./g. -mole

Ht. Formation HCl (g.) = $\underline{-22.063}$

Ht. Soln. HCl = -17.787 kcal./g. -mole

Ht. Soln. HCl/lb. $= (-17.787)(\frac{1800}{36.5})$

$=$ 877 Btu/lb.

Soln. Ht. Generated $= (877)(17.22)$

$=$ 15,080 Btu/hr.

Total Heat Load $=$ 12,262,000 + 15,080

$=$ 12,277,080 Btu/hr.

Water t = $175^\circ - 50^\circ$F. = 125°F.

Feed Water $= \frac{12,277,080 \text{ Btu/hr.}}{(125)}$

$=$ 98,250 lb./hr.

$=$ 196.5 GPM

Water leaving Adiabatic
Saturation Section $=$ 98,250 - 11,690

$=$ 86,560 lb./hr.

$=$ 173.1 GPM

6. HCl Absorption Check

Assume H_2O enters and leaves adiabatic quench section at 175°F. Therefore, equilibrium check on HCl will be at 175°F. liquid vs. 191°F. saturated combustion gas.

$$p_{HCl} \text{ in gas} = \frac{\text{moles HCl/hr.}}{\text{moles BDG/hr.} + \text{moles } H_2O\text{/hr.}}$$

$$= \frac{(0.472)(760)}{(321.15 + (11,777.3/18))}$$

p_{HCl} = 0.368 mm. Hg

Liquid Concn. $= \frac{17.22}{98,250}(100)$

$= 0.01752$ wt. %

From Perry (1963) p. 14-6, @ 80°C., 2% by weight HCl has an equilibrium

$p^*_{HCl} = 0.0245$ mm. Hg

$(p_{HCl})_{gas} > p^*_{HCl}$; and absorption driving force is positive throughout tower.

7. Tower Area

Design is for 70% of flood, using general equation

$$(G_o/\phi)_F = k\,(1 - m(L_o/\rho_L)^{0.57})(\sigma/\sigma_w)^n$$

Because the lower the ϕ - value, the lower the G_o required for flood, design is based on the lowest tower ϕ - value, which corresponds to gas density at the top end of the adiabatic saturation section, which is also the point of maximum weight rate of gas flow.

gas density, sat'd. @ 191.2°F. $= \left(\frac{2.184 \text{ lbs.}}{47.27 \text{ CF}}\right)$

$= 0.0462$ lb./CF

$$\phi = \left(\frac{0.0462}{0.075}\right)^{0.5} = 0.785$$

Assume 1-1/2" Berl Saddles: (low range $(L_o//\rho_L)$)

(Go to larger size if final ΔP is too high.)

From Table 3-1 $k = 2740$

$m = 2.13 \times 10^{-2}$

for aqueous system $(\sigma/\sigma_w) = 1.0$

and $(G_o)_F = (0.785)(2740)(1 - 0.0213(L_o//\rho_L)^{0.57})$

max. liquid rate = 98,250 lb./hr.

Trial No. 1: Take Area = 30 ft.^{2}

$$L_o = \frac{98,250}{30} = 3,275 \text{ lb./hr./ft.}^2$$

and $(G_o)_F = (0.785)(2740)(0.796)$

$= 1713$ lb./hr./ft.^{2}

$$(G_o)_{act} = \frac{9885 + 11,777}{30}$$

$= 722$ lb./hr./ft.^{2}

$R = ((G_o)_{act}/(G_o)_F)(722/1713)$

$= 0.422$ too low.

Trial No. 2: Take $A_2 = (0.422/0.7)(30)$

$= 18.1$ ft.^{2}

Adjust A_2 = 19.63 ft.^{2} for 5' Diam. Tower

$$L_o = \left(\frac{98,250}{19.63}\right) = 5000 \text{ lb./hr./ft.}^2$$

$(L_o/\rho_L) = (5000/62.4) = 80.1$

$(G_o)_F = (0.785)(2746)(0.74)$

$= 1592$ lb./hr./ft.^{2}

$$(G_o)_{act} = (722)(30/19.63)$$

$$= 1104 \text{ lb./hr./ft.}^2$$

$$R = (G_o)_{act}/(G_o)_F = (1104/1592)$$

$$= 0.694$$

Diam. = 5'-0" for 1-1/2" Berl Saddles

(Note: On review of design, client requested 50% excess combustion gas scrubbing capacity to provide for possible peak organic disposal rate, and accordingly, diameter was revised to 6'-0".)

For 6'-0" Diam., A = 28.3 ft.^{2}

$$L_o = (5000)\left(\frac{19.63}{28.3}\right) = 3470 \text{ lb./hr./ft.}^2$$

$$G_o = (1104)\left(\frac{19.63}{28.3}\right) = 765 \text{ lb./hr./ft.}^2$$

8. Packed Height

A. Adiabatic Saturation Section, Gas-Film Controls

Assume gas enters and leaves section at 175°F.

$$(N_G)_h = \frac{t_2 - t_1}{(\Delta t)_m} = \ln\left(\frac{1425}{16.2}\right)$$

$$= 4.47 \text{ Transfer Units}$$

$(H_G)_h$: for : L_o = 3470, G_o = 765, from Fellinger data, Sherwood and Pigford (1952).

$$(H_G)_{NH_3} = 0.9 \text{ ft.}$$

$$(H_G)_{H_2O} = (0.90)(0.60/0.61)^{0.5} = 0.90 \text{ ft.}$$

$$(H_G)_h = (0.90)(D/\alpha)^{0.5}(\mu_d/\mu_h)^{0.27}(\rho_h/\rho_d)^{0.84}(\sigma_h/\sigma_d)^{0.95-0.262 \log L_o}$$

Temperatures

Parameter	$70^oF.$	$130^oF.$	$175^oF.$	$191^oF.$
U_{air}, cp	0.018	0.0192		0.0205
$o_{air}^{(wet)}$	0.0742	0.0636	0.0517	0.0462
o_{H_2O}	72.8		63.	

Because $0.262 \log L_o > 0.925$, o correction drops out

and
$$(H_G)_h = (0.90)(1.291)\left(\frac{0.018}{0.0205}\right)^{0.27}\left(\frac{0.0462}{0.0742}\right)^{0.84}$$
$$= (0.90)(1.291)(0.965)(0.67)$$
$$= 0.75 \text{ ft.}$$
$$Z_{as} = (H_G)_h\ (N_G)_h$$
$$= (0.75)(4.47)$$
$$Z_{as} = 3.35 \text{ ft.}$$

B. Cooling-Condensing

Design convention for the case where the liquid $\Delta t >$ gas Δt through the cooling section assumes that liquid film controls. In this case:

$$(N_L)_h = \frac{(t_2 - t_1)}{(T_2 - t_2) - (T_1 - t_1)} \ln\left(\frac{T_2 - t_2}{T_1 - t_1}\right)$$
$$= \frac{(175 - 50)}{(130 - 50) - (191.2 - 175)} \ln\left(\frac{80}{16.2}\right)$$
$$= \left(\frac{125}{63.8}\right)(1.6)$$
$$= 3.13 \text{ Transfer Units}$$

$(H_L)_h$ Estimation

from the Wilke-Cheng (1963) correlation:

$(H_L)_h = (H_L)_d(D/\alpha)^{0.5}(\mu_h/\mu_d)^{0.55}(\rho_d/\rho_h)^{.329}(\sigma_h/\sigma_d)^{0.554 - 0.157 \log L}$

$0.157 \log L > 0.554$, σ correction does not apply.

From O_2 desorption data of Sherwood and Holloway (1940)

at $L_o = 3470$ $(H_L)_d = 0.95$ ft.

$G_o = 765$

$(P_r/S_c)^{0.5} = (1.0/0.60)^{0.5} = 1.291$

$(\mu_h/\mu_d)^{0.55} = (0.018/0.0185)^{0.55} = 0.986$

$(\rho_d/\rho_h)^{0.329} = (0.0742/0.0668)^{0.329} = 1.035$

$(H_L)_h = (0.95)(1.291)(0.986)(1.035)$

$= 1.25$ ft.

Packed Height $= (1.25)(3.13)$ $Z_L = 3.92$ ft.

Total Theoretical Packed Height $= (Z)_{as} + (Z)_C$

$Z_T = 3.35 + 3.92$

$Z_T = 7.27$ Ft.

Using a 50% Safety Factor: Packed Height = 11.5 Ft.

9. Pressure Drop

ΔP for packing

$L_o/\rho_L = (3470/62.4) = 55.7$

Operation with respect to loading

$(G_o/\emptyset)_L = 1454\ (1 - 1.755 \times 10^{-2}\ (55.7)^{0.55})$

$= 1454\ (0.84)$

$= 1222$ lb./hr./ft.^{2}

$(765/1222)\ (100) = 62.5\%$ of loading G_o

so $(\Delta P/Z) = a_1\ (G_o/\emptyset)^{1.8}$

and from Appendix:

$$a_1 = 7.90 \times 10^{-7}\ (10^{2.13 \times 10^{-3}(L_o/\rho_L)})$$

$$a_1 = 7.90 \times 10^{-7}\ (10^{0.183})$$

$$= 1.202 \times 10^{-6}$$

$$(\Delta P/Z) = (1.202 \times 10^{-6})\ (765)^{1.8},\ \emptyset = 1.0$$

$$= (1.202)\ (0.156)$$

$$= 0.1875 \text{ in. } H_2O/\text{Ft.}$$

for entrainment separator section:

$$(\Delta P/Z)_{dry} = 4.28 \times 10^{-7}\ (G_o/\emptyset)^{1.8}$$

$$= 0.0668''$$

(a) ΔP Packing, intrinsic = (0.1875)(11.5) = 2.16"

(b) ΔP Entrain. Sep., 9" of 1-1/2" B.S. = (0.75)(0.0668) = 0.05"

*(c) ΔP Packing Supports, for (a) & (b) = (2)(0.11) = 0.22"

*(d) ΔP Distributor = 0.11"

(e) Entry & Exit Loses = 0.40"

2.94" H_2O

Allowance for possible fouling = 50%

and (1.5)(2.94) = 4.40" H_2O Total

V. CONCLUSIONS AND RECOMMENDATIONS

Review of the incinerator-scrubbing design technology, as applied to the combustion and possible emission of hydrocarbons, indicates that the data design base is very unevenly developed. New and highly accurate design correlations are available for estimating the packed-tower diameter and packing pressure drop, while on the other hand, estimation techniques for countercurrent contact path or packing height are grossly inadequate because of the lack of a design data base.

Tower design for waste combustion systems consists of two distinct heat transfer problems: sizing and adiabatic quench section and sizing the subsequent cooling-condensing-absorption section. Both sections normally are encompassed by a single scrubbing-quench unit, but the design approach to each section is different. The design methods explored include estimation of the height requirements for the adiabatic section using an NTU based on temperature driving force, together with the assumption that gas-film controls. Contact height estimation for the direct-contact cooling-condensing region of a scrubber is made on the assumption that liquid-film resistance to heat transfer controls, an assumption that empirically yields rational contact heights, but which is theoretically unjustifiable (Wilke et al, 1963).

Despite the widespread use of direct-contact cooling-condensing-absorbing equipment for the control of emissions from incinerator off-gases, the data base available for rational design is virtually non-existent. Remedial research programs are needed in the following areas:

1. Experimental determination of HTU for direct-contact countercurrent gas-water contacting equipment, with simultaneous determination of the HTU for the following three different transfer potentials:

   (a) Enthalpy
   (b) Humidity (partial pressure of H_2O)
   (c) Temperature

2. Inter-correlation of overall mass and heat transfer coefficients on the basis of individual film resistances, so that direct-contact overall coefficients can be estimated from presently-available literature data.

3. Determination of the effect of liquid-film heat transfer resistance in direct-contact cooling-condensing operations over appreciable temperature ranges.

4. Experimental determination of the effects of fog formation on heat and mass transfer coefficients in direct-contact cooling-condensing operations, and on the efficiency of particulate removal in such operations.

TABLE A-1

INTRINSIC PRESSURE DROP EQUATIONS

3/4-INCH CERAMIC RASCHIG RINGS

Critical Gas Sweep Liquid Rate: $(L_o/\rho_L) = 136.5$

Loading: $(G_o/\emptyset)_{L'} = 674(1 - 1.493 \times 10^{-2}(L_o/\rho_L)^{0.62})$

Flooding: Low Range: $(L_o/\rho_L) < 136.5$

$$(G_o/\emptyset)_F = 1685(1 - 3.53 \times 10^{-2}(L_o/\rho_L)^{0.57})(\sigma/\sigma_w)^n$$

High Range: $(L_o/\rho_L) > 136.5$

$$(G_o/\emptyset)_F = 1518(1 - 3.28 \times 10^{-2}(L_o/\rho_L)^{0.57})(\sigma/\sigma_w)^n$$

$n = 0.58$ for $(L_o/\rho_L) < 136.5$

$n = 1.0$ for $(L_o/\rho_L) > 136.5$

Zone 1. Pre-Load and Pre-Critical:

$$(G_o/\emptyset) < (G_o/\emptyset)_{L'} \; ; \; (L_o/\rho_L) < 136.5$$

$$(\Delta P/N) = a_1 (G_o/\emptyset)^{1.8}$$

where $a_1 = 2.64 \times 10^{-6} (10^{4.83 \times 10^{-3}(L_o/\rho_L)})$

Zone 2. Pre-Load and Super-Critical:

$$(G_o/\emptyset) < (G_o/\emptyset)_{L'} \; ; \; (L_o/\rho_L) > 136.5$$

$$(\Delta P/N) = a_2 (G_o/\emptyset)^{1.8} + K_1$$

where $a_2 = 2.18 \times 10^{-6} (10^{5.12 \times 10^{-3}(L_o/\rho_L)})$

$K_1 = 5.15 \times 10^{-6} (L_o/\rho_L)^{1.90}$

3/4-INCH CERAMIC RASCHIG RINGS Cont'd.

Zone 3. Load-to-Flood and Pre-Critical:

$$(G_o/\phi)_F > (G_o/\phi) > (G_o/\phi)_{L'} ;\ (L_o/\rho_L) < 136.5$$

$$(\Delta P/N) = a_3 (G_o/\phi)^{3.0}$$

where $a_3 = 1.01 \times 10^{-9}(10^{6.47 \times 10^{-3}(L_o/\rho_L)})$

Zone 4. Load-to-Flood and Super-Critical:

$$(G_o/\phi)_F > (G_o/\phi) > (G_o/\phi)_{L'} ;\ (L_o/\rho_L) > 136.5$$

$$(\Delta P/N) = a_4 (G_o/\phi)^{3.0} + K_2$$

where $a_4 = 8.64 \times 10^{-10}(10^{6.38 \times 10^{-3}(L_o/\rho_L)})$

$K_2 = 3.68 \times 10^{-3} (L_o/\rho_L)^{0.75}$

TABLE A-2

INTRINSIC PRESSURE DROP EQUATIONS

1-INCH CERAMIC RASCHIG RINGS

Critical Gas Sweep Liquid Rate: $(L_o/\rho_L)_c = 144.5$

Loading: $(G_o/\phi)_L = 935(1 - 2.44 \times 10^{-2}(L_o/\rho_L)^{0.621}$

Flooding: Low Range: $(L_o/\rho_L) < 144.5$

$$(G_o/\phi)_F = 1870(1 - 3.65 \times 10^{-2}(L_o/\rho_L)^{0.57})(\sigma/\sigma_w)^n$$

High Range: $(L_o/\rho_L) > 144.5$

$$(G_o/\phi)_F = 1420(1 - 2.81 \times 10^{-2}(L_o/\rho_L)^{0.57})(\sigma/\sigma_w)^n$$

$n = 0.58$ for $(L_o/\rho_L) < 144.5$

$n = 1.0$ for $(L_o/\rho_L) > 144.5$

Zone 1. Pre-Load and Pre-Critical:

$$(G_o/\phi) < (G_o/\phi)_L ; (L_o/\rho_L) < 144.5$$

$$(\Delta P/N) = a_1 (G_o/\phi)^{1.8}$$

where $a_1 = 1.29 \times 10^{-6} (10^{6.60 \times 10^{-3}(L_o/\rho_L)})$

Zone 2. Pre-Load and Super-Critical:

$$(G_o/\phi) < (G_o/\phi)_L ; (L_o/\rho_L) > 144.5$$

$$(\Delta P/N) = a_2 (G_o/\phi)^{1.8} + K_1$$

where $a_2 = 2.57 \times 10^{-6} (10^{3.67 \times 10^{-3}(L_o/\rho_L)})$

$K_1 = 1.70 \times 10^{-6} (L_o/\rho_L)^{2.24}$

1-INCH CERAMIC RASCHIG RINGS Cont'd.

Zone 3. **Load-to-Flood and Pre-Critical:**

$$(G_o/\emptyset)_F > (G_o/\emptyset) > (G_o/\emptyset)_L \; ; \; (L_o/\rho_L) < 144.5$$

$$(\Delta P/N) = a_2 \, (G_o/\emptyset)^{3.0}$$

where $a_2 = 6.95 \times 10^{-10} \, (10^{6.42 \times 10^{-3}(L_o/\rho_L)})$

Zone 4. **Load-to-Flood and Super-Critical:**

$$(G_o/\emptyset)_F > (G_o/\emptyset) > (G_o/\emptyset) \; ; \; (L_o/\rho_L) > 144.5$$

$$(\Delta P/N) = a_3 \, (G_o/\emptyset)^{3.0} + K_2$$

where $a_3 = 9.11 \times 10^{-10} \, (10^{4.77 \times 10^{-3}(L_o/\rho_L)})$

$K_2 = 3.63 \times 10^{-4} \, (L_o/\rho_L)^{1.35}$

TABLE A-3

INTRINSIC PRESSURE DROP EQUATIONS

1-1/2-INCH CERAMIC RASCHIG RINGS
(3/16" WALL)

Critical Gas Sweep Liquid Rate: $(L_o/\rho_L) = 209$

Loading: $(G_o/\phi)_{L'} = 1070(1 - 2.14 \times 10^{-2}(L_o/\rho_L)^{0.62})$

Flooding: Low Range: $(L_o/\rho_L) < 209$

$$(G_o/\phi)_F = 2118(1 - 2172 \times 10^{-2}(L_o//\rho_L)^{0.57})\ (\sigma/\sigma_w)^n$$

High Range: $(L_o/\rho_L) > 209$

$$(G_o/\phi)_F = 1500(1 - 1.875 \times 10^{-2}(L_o/\rho_L)^{0.57})\ (\sigma/\sigma_w)^n$$

$n = 0.58$ for $(L_o/\rho_L) < 209$

$n = 1.0$ for $(L_o//\rho_L) > 209$

Zone 1. Pre-Load and Pre-Critical:

$$(G_o/\phi) < (G_o/\phi)_{L'}\ ;\ (L_o/\rho_L) < 209$$

$$(\Delta P/N) = a_1 (G_o/\phi)^{1.8}$$

where $a_1 = 1.45 \times 10^{-6} (10^{2.60 \times 10^{-3}(L_o//\rho_L)})$

Zone 2. Pre-Load and Super-Critical:

$$(G_o/\phi) < (G_o/\phi)_{L'}\ ;\ (L_o//\rho_L) > 209$$

$$(\Delta P/N) = a_2 (G_o/\phi)^{1.8} + K_1$$

where $a_2 = 2.83 \times 10^{-6} (10^{2.035 \times 10^{-3}(L_o//\rho_L)})$

$K_1 = 1.38 \times 10^{-11} (L_o/\rho_L)^{3.72}$

1-1/2-INCH CERAMIC RASCHIG RINGS Cont'd.
(3/16" WALL)

Zone 3. Load-to-Flood and Pre-Critical:

$(G_o/\emptyset)_F > (G_o/\emptyset) > (G_o/\emptyset)_L \; ; \; (L_o/\rho_L) < 209$

$(\Delta P/N) = a_3 (G_o/\emptyset)^{3.0}$

where $a_3 = 4.40 \times 10^{-10} (10^{4.10 \times 10^{-3}(L_o/\rho_L)})$

Zone 4. Load-to-Flood and Super-Critical:

$(G_o/\emptyset)_F > (G_o/\emptyset) > (G_o/\emptyset)_{L'} \; ; \; (L_o/\rho_L) > 209$

$(\Delta P/N) = a_4 (G_o/\emptyset)^{3.0} + K_2$

where $a_4 = 5.77 \times 10^{-10} (10^{2.98 \times 10^{-3}(L_o/\rho_L)})$

$K_2 = 4.55 \times 10^{-5} (L_o/\rho_L)^{1.50}$

TABLE A-4

INTRINSIC PRESSURE DROP EQUATIONS

2-INCH CERAMIC RASCHIG RINGS

Critical Gas Sweep Liquid Rate: $(L_o/\rho_L) = 240$

Loading: $(G_o/\phi)_{L'} = 1070\,(1 - 2.14 \times 10^{-2}(L_o/\rho_L)^{0.62})$

Flooding: Low Range: $(L_o/\rho_L) < 240$

$(G_o/\phi)_F = 2280(1 - 2.33 \times 10^{-2}(L_o/\rho_L)^{0.57})(\sigma/\sigma_w)^n$

High Range: $(L_o/\rho_L) > 240$

$(G_o/\phi) = 2060(1 - 2.28 \times 10^{-2}(L_o/\rho_L)^{0.57})(\sigma/\sigma_w)^n$

$n = 0.58$ for $(L_o/\rho_L) < 240$

$n = 1.0$ for $(L_o/\rho_L) > 240$

Zone 1. Pre-Load and Pre-Critical:

$(G_o/\phi) < (G_o/\phi)_{L'}\,;\ (L_o/\rho_L) < 240$

$(\Delta P/N) = a_1\,(G_o/\phi)^{1.8}$

where $a_1 = 1.00 \times 10^{-6}(10^{3.05 \times 10^{-3}(L_o/\rho_L)})$

Zone 2. Pre-Load and Super-Critical:

$(G_o/\phi) < (G_o/\phi)_{L'}\,;\ (L_o/\rho_L) > 240$

$(\Delta P/N) = a_2\,(G_o/\phi)^{1.8} + K_1$

where $a_2 = 1.265 \times 10^{-6}(10^{2.36 \times 10^{-3}(L_o/\rho_L)})$

$K_1 = 8.27 \times 10^{-15}(L_o/\rho_L)^{5.3}$

2-INCH CERAMIC RASCHIG RINGS Cont'd.

Zone 3. Load-to-Flood and Pre-Critical:

$$(G_o/\phi)_F > (G_o/\phi) > (G_o/\phi)_{L'} \; ; \; (L_o/\rho_L) < 240$$

$$(\Delta P/N) = a_3 \, (G_o/\phi)^{3.0}$$

where $a_3 = 2.55 \times 10^{-10} \left(10^{3.91 \times 10^{-3}(L_o/\rho_L)}\right)$

Zone 4. Load-to-Flood and Super-Critical:

$$(G_o/\phi)_F > (G_o/\phi) > (G_o/\phi)_{L'} \; ; \; (L_o/\rho_L) > 240$$

$$(\Delta P/N) = a_4 \, (G_o/\phi)^{3.0} + K_2$$

where $a_4 = 4.33 \times 10^{-10} \left(10^{2.51 \times 10^{-3}(L_o/\rho_L)}\right)$

$K_2 = 7.02 \times 10^{-5} \, (L_o/\rho_L)^{1.43}$

TABLE A-5

INTRINSIC PRESSURE DROP EQUATIONS

3/4-INCH CERAMIC BERL SADDLES

Critical Gas Sweep Liquid Rate: $(L_o/\rho_L) = 160$

Loadings: Low Range: $(G_o/\phi)_{L'} = 748\ (1 - 2.01 \times 10^{-2}\ (L_o/\rho_L)^{0.62})$

High Range: $(G_o/\phi)_{L'} = 453\ (1 - 1.80 \times 10^{-2}\ (L_o/\rho_L)^{0.62})$

Flooding: Low Range: $(L_o/\rho_L) < 160$

$(G_o/\phi)_F = 1825\ (1 - 3.17 \times 10^{-2}\ (L_o/\rho_L)^{0.57})(\sigma/\sigma_w)^n$

High Range: $(L_o/\rho_L) > 160$

$(G_o/\phi)_F = 1405\ (1 - 2.70 \times 10^{-2}\ (L_o/\rho_L)^{0.57})\ (\sigma/\sigma_w)^n$

$n = 0.58$ for $(L_o/\rho_L) < 160$

$n = 1.0$ for $(L_o/\rho_L) > 160$

Zone 1. Pre-Load and Pre-Critical:

$(G_o/\phi) < (G_o/\phi)_{L'}\ ;\ (L_o/\rho_L) < 160$

$(\Delta P/N) = a_1\ (G_o/\phi)^{1.8}$

where $a_1 = 2.08 \times 10^{-6}\ (10^{3.25 \times 10^{-3}(L_o/\rho_L)})$

Zone 2. Pre-Load and Super-Critical:

$(G_o/\phi) < (G_o/\phi)_{L'}\ ;\ (L_o/\rho_L) > 160$

$(\Delta P/N) = a_2\ (G_o/\phi)^{1.8} + K_1$

where $a_2 = 1.379 \times 10^{-6}\ (10^{4.68 \times 10^{-3}(L_o/\rho_L)})$

$K_1 = 5.77 \times 10^{-9}\ (L_o/\rho_L)^{3.0}$

3/4-INCH CERAMIC BERL SADDLES Cont'd.

Zone 3. Load-to-Flood and Pre-Critical:

$$(G_o/\phi)_F > (G_o/\phi) > (G_o/\phi)_L \; ; \; (L_o/\rho_L) < 160$$

$$(\Delta P/N) = a_3 \, (G_o/\phi)^{2.75}$$

where $a_3 = 2.71 \times 10^{-9} \left(10^{5.607 \times 10^{-3}(L_o/\rho_L)}\right)$

Zone 4. Load-to-Flood and Super-Critical:

$$(G_o/\phi)_F > (G_o/\phi) > (G_o/\phi)_L \; ; \; (L_o/\rho_L) > 160$$

$$(\Delta P/N) = a_4 \, (G_o/\phi)^{2.75} + K_2$$

where $a_4 = 1.018 \times 10^{-8} \left(10^{2.20 \times 10^{-3}(L_o/\rho_L)}\right)$

$K_2 = 1.283 \times 10^{-5} \, (L_o/\rho_L)^{1.9}$

TABLE A-6

INTRINSIC PRESSURE DROP EQUATIONS

1-INCH CERAMIC BERL SADDLES

Critical Gas-Sweep Liquid Rate: $(L_o/\rho_L)_c = 176.5$

Loading: $(G_o/\phi)_L = 1354\,(1 - 2.43 \times 10^{-2}\,(L_o/\rho_L)^{0.552})$

Flooding: $(G_o/\phi)_F = 2360\,(1 - 2.64 \times 10^{-2}\,(L_o/\rho_L)^{0.57})\,(\sigma/\sigma_w)^n$

$n = 0.58$ for $L_o/\rho_L < 176.5$

$n = 1.0$ for $L_o/\rho_L > 176.5$

Zone 1. Pre-Load and Pre-Critical:

$(G_o/\phi) < (G_o/\phi)_L\,;\ (L_o/\rho_L) < 176.5$

$(\Delta P/N) = a_1\,(G_o/\phi)^{1.8}$

where $a_1 = 1.34 \times 10^{-6}\,(10^{3.34 \times 10^{-3}(L_o/\rho_L)})$

Zone 2. Pre-Load and Super-Critical:

$(G_o/\phi) < (G_o/\phi)_L\,;\ (L_o/\rho_L) > 176.5$

$(\Delta P/N) = a_2\,(G_o/\phi)^{1.8} + K_1$

where $a_2 = 2.28 \times 10^{-6}\,(10^{2.06 \times 10^{-3}(L_o/\rho_L)})$

$K_1 = 4.98 \times 10^{-12}\,(L_o/\rho_L)^{4.3}$

1-INCH CERAMIC BERL SADDLES Cont'd.

Zone 3. Load-to-Flood and Pre-Critical:

$$(G_o/\emptyset)_F > (G_o/\emptyset) > (G_o/\emptyset)_L \; ; (L_o/\rho_L) < 176.5$$

$$(\Delta P/N) = a_3 (G_o/\emptyset)^{3.0}$$

where $a_3 = 2.83 \times 10^{-10} \left(10^{4.51 \times 10^{-3}(L_o/\rho_L)}\right)$

Zone 4. Load-to-Flood and Super-Critical:

$$(G_o/\emptyset)_F > (G_o/\emptyset) > (G_o/\emptyset)_L \; ; (L_o/\rho_L) > 176.5$$

$$(\Delta P/N) = a_4 (G_o/\emptyset)^{3.0} + K_2$$

where $a_4 = 5.08 \times 10^{-10} \left(10^{3.42 \times 10^{-3}(L_o/\rho_L)}\right)$

$K_2 = 1.425 \times 10^{-5} (L_o/\rho_L)^{1.67}$

TABLE A-7

INTRINSIC PRESSURE DROP EQUATIONS

1-1/2-INCH CERAMIC BERL SADDLES

Critical Gas-Sweep Liquid Rate: $(L_o/\rho_L)_c = 285$

Loading: $(G_o/\phi)_L = 1454\ (1 - 1.755 \times 10^{-2}\ (L_o/\rho_L)^{0.55})$

Flooding: $(G_o/\phi)_F = 2740\ (1 - 2.13 \times 10^{-2}\ (L_o/\rho_L)^{0.57})\ (\sigma/\sigma_w)^n$

Both above equations apply to $(L_o/\rho_L) < 285$

$n = 0.58$ for $(L_o/\rho_L) < 285$

$n = 1.0$ for $(L_o/\rho_L) > 285$

Zone 1. Pre-Load and Pre-Critical:

$(G_o/\phi) < (G_o/\phi)_L\ ;\ (L_o/\rho_L) < 285$

$(\Delta P/N) = a_1\ (G_o/\phi)^{1.8}$

where $a_1 = 7.90 \times 10^{-7}\ (10^{2.13 \times 10^{-3}(L_o/\rho_L)})$

Zone 3.* Load-to-Flood and Pre-Critical:

$(G_o/\phi)_F > (G_o/\phi) > (G_o/\phi)_L\ ;\ (L_o/\rho_L) < 285$

$(\Delta P/N) = a_3 (G_o/\phi)^{3.0}$

where $a_3 = 1.612 \times 10^{-10}\ (10^{2.97 \times 10^{-3}(L_o/\rho_L)})$

*No data available for Zones 2 & 4 Super-Critical Operation.

TABLE A-8

INTRINSIC PRESSURE DROP EQUATIONS

2-INCH CERAMIC BERL SADDLES

Critical Gas Sweep Liquid Rate: $(L_o/\rho_L) = 300$

Loading: $(G_o/\emptyset)_L = 1692\,(1 - 1.17 \times 10^{-2}(L_o/\rho_L)^{0.55})$

Flooding: Low Range: $(L_o/\rho_L) < 300$

$(G_o/\emptyset)_F = 3110(1 - 1.866 \times 10^{-2}(L_o/\rho_L)^{0.57})\,(\sigma/\sigma_w)^n$

High Range: $(L_o/\rho_L) > 300$

$(G_o/\emptyset)_F = 2715(1 - 1.532 \times 10^{-2}(L_o/\rho_L)^{0.57})\,(\sigma/\sigma_w)^n$

$n = 0.58$ for $(L_o/\rho_L) < 300$

$n = 1.00$ for $(L_o/\rho_L) > 300$

Zone 1. Pre-Load and Pre-Critical:

$(G_o/\emptyset) < (G_o/\emptyset)_L\ ;\ (L_o/\rho_L) < 300$

$(\Delta P/N) = a_1\,(G_o/\emptyset)^{1.8}$

where $a_1 = 4.28 \times 10^{-7}(10^{3.57 \times 10^{-3}(L_o/\rho_L)})$

Zone 3*. Load-to-Flood and Pre-Critical:

$(G_o/\emptyset)_F > (G_o/\emptyset) > (G_o/\emptyset)_L\ ;\ (L_o/\rho_L) < 300$

$(\Delta P/N) = a_3\,(G_o/\emptyset)^{3.0}$

where $a_3 = 7.44 \times 10^{-11}(10^{3.46 \times 10^{-3}(L_o/\rho_L)})$

*No data available for Zones 2 and 4 Super-Critical operation.

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APPENDIX F

PARTICULATE-SCRUBBING SYSTEMS
FOR
HYDROCARBON EMISSION CONTROL

F.53

SUMMARY

Based on the initial finding that the major stationary-source emission of hydrocarbons was attributable to combustion processes, and the fact that these processes emitted both carcinogenic heavy hydrocarbons and particulates, attention was focused on controls for combustion process emissions. Review of control technology in this area showed that wet scrubbing, although widely-used, had an inadequate design or performance assessment base, and was characterized by an extreme dichotomy between a highly-developed inertial impaction theory and an absence of a rational engineering design basis. In view of the literature finding that the carcinogenic polynuclear hydrocarbon fractions, such as benzo(a)pyrene, emitted by combustion operations follows the path of the particulates in any control process, correlation of wet scrubber performance for particulate/hydrocarbon removal was undertaken.

When dispersed-liquid wet scrubber performance data were reviewed in terms of a mechanism of turbulent agglomeration contacting and secondary inertial removal, rather than inertial impaction alone, it was found that there were three primary independent variables: inlet dust loading, water/gas ratio, and gas velocity (or pressure drop equivalent). It was further found that when scrubber performance was expressed in terms of the percent mass penetration, the performance was inversely proportional to both the inlet dust loading, C_d, and the liquid/gas ratio, (W/G). When the latter variables were combined into a single product group, termed the "agglomeration index", (C_d) (W/G), it was found that literature data on wet scrubber dust penetration showed penetration to be inversely proportional to the agglomeration index. Application of this new concept to a wide range of experimental and field data on wet scrubber performance showed the agglomeration index to be a highly-sensitive and very powerful general correlating parameter. Deviations from the agglomeration index correlation were found to be indicative of dust feed pre-agglomeration or design deficiencies in the removal mechanism (as distinguished from contacting mechanism) of the scrubber.

The final primary variable of pressure drop, ΔP, was found to be readily correlated when performance data were plotted at constant agglomeration index conditions, and the final generalized equation obtained was:

$$\% \text{ Penetration} = \frac{K(\Delta P)^{-n}}{(C_d)(W/G)}$$

where n = 1 or 2, depending on the flow regime, and K is the performance constant characterizing the relative capability of the scrubber. This correlating equation allows, for the first time, valid absolute performance comparisons between scrubbers, and establishes the test or operating conditions necessary to validate such comparisons.

It is apparent that established inertial impaction theory fails to satisfactorily describe the scrubber variable behavior found in this investigation, and there is ample reason to doubt that this theory, in its present form, applies to wet scrubber performance description. While it is demonstratd that the data behavior is in accord with proposed turbulent agglomeration mechanisms, corollary quantitative theoretical support is still to be developed. In this respect, the engineering analysis of scrubber performance and the predictive capability of the correlating equation has temporarily advanced empiricism beyond the present reach of theory.

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I. INTRODUCTION

The purpose of this study was to identify and evaluate control techniques for the prevention or removal of hydrocarbon emissions from stationary sources, with the ultimate objective of identifying gaps in methodology or design procedures and formulating remedial experimental programs. A review of the open literature on hydrocarbon emission control methods showed that, aside from the compilation, Air Pollution Engineering Manual (HEW, 1967), there is very little in the way of published quantitative industrial application information for control processes or equipment. A general review of the background control art has recently been presented by HEW (1970) in their manual, Control Techniques for Hydrocarbons and Organic Solvent Emissions from Stationary Sources, but this treatment is largely qualitative.

The crux of the control evaluation problem was identified in a recently-completed specific study of heavy hydrocarbon emission. In their preliminary report on Control Techniques for Polycyclic Organic Matter Emissions, GCA Technology (1970), after considering the available quanitative design data, stated, "in the absence therefore of any practical information on the effects of existing types of gas cleaning equipment on polycyclic organic emissions, we must rely on theoretical considerations to determine which cleaning techniques will be effective in removing polycyclic organic emissions". While the state-of-the-art outlook for control technology for certain hydrocarbon classes other than polycyclic hydrocarbons is not quite this bleak, the degree of control effectiveness offered by a specific design for a specific emission is still uncertain in the best of cases.

Control effectiveness uncertainties may result in many instances from a variable definition of pollution, or failure to measure the process output under operative controls. An example is provided by the review of Fawcett (1970) of the emissions common to phthalic anhydride manufacturing industry, and the nature of the controls used. The emissions are the acids or acid anhydrides, aldehydes, o-xylene or naphthalene, and occasionally, particulates. In one set of locations, the air pollution problem is that of nuisance odors and lachrymatory compounds, which are characteristic of the organic acid components. On the other hand, in West Coast locations, or others with poor air shed ventilation, the pollution problem is that caused by the photochemically-reactive smog-forming aldehyde and aromatic constituents. Wet scrubbing is reported by Fawcett to afford 99% removal of the acids and anhydrides, but to give relatively poor control of the aldehydes. Thus, in smog-prone areas where the aldehyde is the primary concern, "control" would involve incineration of the process off-gas, either by direct-flame or catalytic means, while "control" in other areas would call for acid removal by wet scrubbing. Control effectiveness is therefore measurable only in the context of a variable local pollution problem. With a limited number of exceptions, the health and pollution hazards of specific organic compounds have not been fully determined, and until these basic parameters are defined, control effectiveness cannot be absolutely fixed. Thus, quantitative design and "efficiency" information for existing control techniques can only be assembled on a "case-history" basis. This type of information can be obtained by (a) soliciting information on successful field installations, (b) utilization of unpublished information from the files of engineering firms in the emission control field, or (c)development of original design techniques by organization and evaluation of published experimental and field data in a defined control area. The latter two avenues were the ones chosen for implementation in this program.

II. DEFINITION OF CONTROL PROBLEM

A. CONTROL TECHNOLOGY STATE-OF-THE-ART

The starting point of this program was the publication, Control Techniques for Hydrocarbon and Organic Solvent Emissions from Stationary Sources (HEW, 1970). A review of this compilation and supporting literature indicated that applicable technology for the control of hydrocarbon emissions was very unevenly developed. Design methods for techniques such as adsorption and after-burning were available and reasonably straightforward, whereas wet scrubbing methods, including absorption, direct-contact condensation, and wet particulate removal, appeared to lack an adequate design base. This conclusion was partially confirmed by the statement regarding particulate collectors made in the recent control equipment review by the American Industrial Hygiene Association (AIHA, 1968) which states, "when the process is on the drawing board and the collector is to be specified as part of the plant design, the prime recourse is to experience on similar plants and processes". The frequent association of higher molecular-weight hazardous organic fractions with particulate emissions from combustion processes makes this apparent design deficiency of more than academic interest.

Despite the fact that wet scrubbing methods are widely used for particulate and hydrocarbon removal, usually concurrently, an assessment of the present availability of design methods and the general state of technical development of this area showed there to be a very serious deficiency in technology. While the nature of this deficiency is examined in detail in Section 3 of this report, a technical literature review showed that there was an unbridged gap between theory and field practice, and that there was no rationale for scrubber selection or design for the following problem areas:

(a) Removal of liquid hydrocarbon aerosols or of particulates in association with heavy hydrocarbon co-particles, particularly polynuclear hydrocarbons.

(b) Combustion gas scrubbing with secondary absorption of water-soluble oxidized hydrocarbons.

(c) Condensation (direct or indirect) followed by mist-filtration or scrubbing.

Thus, there was an obvious necessity for an intensive critical examination of scrubber technology and a clear mandate for re-evaluation of design approaches and data correlation. This conclusion was supported by a preliminary review of the relative seriousness of hydrocarbon emissions from stationary sources.

B. HYDROCARBON EMISSION AND CONTROL RELEVANCE

At the very outset of this systems study, it became apparent that the major source of stationary hydrocarbon emission was the combustion process. Invariably, such processes emit particulates in association with hydrocarbons. Power generation, the incineration of municipal wastes, and the disposal of industrial organic liquid sludges are examples of such operations. A good deal of attention has been focused on this particular aspect of hydrocarbon-particulate emission because of the indicated health problem attendant on the polycyclic aromatic hydrocarbons normally found in combustion off-gases, particularly in inefficient combustor units. Several of the polycyclic nuclear aromatics, notably benzo(a)pyrene (BaP), are known to be carcinogenic, and for this reason, control information for these hydrocarbons merits priority.

Hangebrauck (1967) measured rates of emission of polynuclear hydrocarbons for refuse burning and various industrial operations, both before and after the exhaust gases passed through control equipment. Data were presented on the effect of CO waste heat boilers and plume burners on catalytic cracking regenerators in petroleum refining, and of water-spray scrubbers and steam "sprays" in batch asphalt hot-road-mix plants. In the latter case, water-spraying was found to be 92% effective in BaP removal, but the data were extremely limited, and no information was given on the design of the control equipment.

Cuffe (1967) studied the emission of seven key polynuclear hydrocarbons from coal-fired power plants using various boiler designs. The most significant finding was the fact that preliminary tests showed that considerable recovery of the polynuclear aromatics was effected by the fly-ash collectors, although no quantitative data were provided. Full-scale tests showed that even formaldehyde followed the particulates, indicating probable adsorption. In terms of control relevance, this means that hydrocarbon emission control for a combustion process can and should be accomplished via particulate control. This restatement of control objective, along with the previously established design gap for wet scrubbers, served to define the priority of control technology assessment as being that of particulate removal by wet scrubbing techniques.

C. SCOPE OF PROGRAM

Initially, the study of wet scrubbing methods for the control of hydrocarbon emissions from stationary sources was considered to be the first phase of an overall control method design workup. However, preliminary efforts on wet scrubber particulate removal data correlation proved so productive that work was continued on this subject to the limit of the project time. As a complementary study, material was assembled on the design of packed scrubbers for incinerator/scrubber trains in cooperation with the engineering staff of the Maurice A. Knight Company of Akron, Ohio. These new and hitherto proprietary design techniques have been presented in a corollary report covering methods for estimating the removal of soluble pollutants such as oxidized hydrocarbons, in a combustion gas quench-cooling operation. A third effort, covering proprietary condensation-mist elimination techniques for controlling certain hydrocarbon solvent emissions, was abandoned when permission to release the data was withdrawn by the cooperating engineering firm.

III. WET SCRUBBER THEORY

Despite the fact that water-scrubbing of combustion gases or other emissions is one of the oldest techniques employed for particulate removal, the contacting mechanisms involved are still not well understood. Consequently, as Semrau (1963) pointed out, "failures have resulted from ignorance of the factors involved in scrubber performance and from the lack of a rational basis for design". A cursory review of the current available literature indicates that this situation still prevails.

A number of recently-published reviews and books have contained sections or chapters ostensibly dealing with wet scrubber design, wherein very little, if any, quantitative design information is presented. HEW AP-51 (1969), Control Techniques for Particulate Air Pollutants, presents an excellent concise review of the various types of wet scrubbing equipment, along with information on the operating and performance ranges of each type. However, although the mechanisms of contacting and operation of the different scrubber types are briefly explored, no generalized design criteria are cited. Similarly, in Chapter 4 of Danielson (1967), dealing with control equipment for particulate matter, the section on wet scrubbers (by E.J. Vincent) contains only qualitative descriptive matter, with no mention of controlling parameters. The same chapter, however, deals fully, and in detail, with design approaches for other equipment such as inertial separators (dry), fibrous filters, and electrostatic units. The AIHA volume of the Air Pollution Manual covering control equipment (Part II, 1968) also confines its discussion of wet scrubbers to descriptive material, augmenting this with Stairmand's (1956) "typical" grade-efficiency curves for wet scrubbers.

At least part of the present unsatisfactory state of development of wet scrubber design art may be attributed to failure to recognize the dual-functionality of the wet scrubber. Thus, Lunde and Lapple (1958) in their state-of-the-art review, speak only of "deposition" mechanisms in wet scrubbers, indicating these to be solely surface collection and removal processes. Only recently, in work such as that of Davis and Truitt (1971), has attention been devoted to the other fundamental scrubber mechanism: that of particle growth by agglomeration. Most wet scrubbers utilize some type of inertial separation force to cause deposition of particles of a minimum size or mass on a surface collector, but the scrubbers also effect particle "growth" to the minimum removal size by contact between water droplets and dust particles. There is also evidence that particle growth by collision processes occurs even for dry centrifugal collectors such as cyclones, and indeed, in the field of atmospheric dust fallout studies, considerable attention has long been given to agglomerative particle growth. The theoretical and experimental work of Langstroth and Gillespie (1947) is of fundamental significance in this latter area, and would appear to have immediate relevance to the interpretation of wet scrubber performance data, and will be considered later in this section.

The inability to isolate the primary contacting mechanisms has resulted in a highly uneven theoretical approach to wet scrubber theory, and the greatest amount of development effort has been devoted to inertial impaction theory and the least attention to turbulent agglomeration theory. Neither theory has been directly and fully tested against performance, and recent sophisticated attempts to compare inertial impaction theory with scrubber performance, such as the computer-assisted experimental investigation conducted by Boll (1971) have proved disappointing. Because the impaction theory appears to have merited the major share of attention and development, it will be considered first.

A. INERTIAL IMPACTION THEORY

The inertial impaction theory, in its quantitative form, was initially set forth Langmuir and Blodgett (1944), and is essentially a "ballistic" collision theory. It is generally assumed that the small dust particulates move with the velocity of the gas stream, and that the larger, slower-moving water droplets serve as collision "targets" for the dust particles. These concepts and elementary equations for the volume and number of particulates swept by a water drop swarm in a scrubber had been considered earlier by Kleinschmidt (1939), but it was assumed that all dust particles in the volume swept by the drops would be captured. Langmuir and Blodgett pointed out that small particles of low enough inertia could follow the flow streamlines around the drop, and introduced the concept of "target efficiency", which is the ratio of the number of particles actually captured by the drop to the total number in the gas volume swept by the drop.

Target efficiency has been defined in terms of various combinations of its controlling variables, but the parameter generally used in the United States is the one suggested by Langmuir and Blodgett (1944):

$$\Psi = \frac{\rho_p D^2{}_p (V_g - V_d)}{18\ \mu\ D_d} \qquad (3\text{-}1)$$

where

Ψ = separation number or inertial impaction parameter, dimensionless

D_d = diameter of water droplet

D_p = diameter of dust particle

V_g, V_d = velocities of gas and water drop respectively

ρ_p = density of dust particle

μ = viscosity of gas

Because target efficiency for drop collectors can be theoretically calculated as a function of the separation number, Ψ, only for viscous flow ($N_{Re}<1$) or potential flow ($N_{Re}>10^3$) ranges with respect to the drops, the relation between target efficiency, E_t, and Ψ is best determined experimentally. Experimental results for rigid spheres have been presented by Ranz and Wong (1952) and for supported liquid drops by Walton and Woolcock (1960). However, as the review of these and other data by Boll (1971) indicates, agreement is only fair. The use of target efficiency vs. inertial parameter plots for calculation of spray chamber contact times for a given dust and water drop size has been demonstrated by Ranz and Wong (1952) who stated the time rate of aerosol concentration change in a uniform spray region as:

$$-dN_p/dt = N_p N_d E_t V_g \pi D_d^2/4 \qquad (3\text{-}2)$$

where

N_p = number concentration of particles, cm^{-3}

N_d = number concentration of drops, cm^{-3}

V_g = relative velocity of droplets through the dust, cm/sec.

D_d = diameter of water droplet, cm.

Integration of Equation (3-2) over a finite holdup time, t, yields a fractional residual, or weight penetration as:

$$F = N_p/N_{po} = \exp(-tV_g N_d E_t \pi D_d^2/4) \qquad (3\text{-}3)$$

Equation (3-3) states that scrubber dust penetration should yield a straight line on a semi-log plot against any of the variables in the right-hand parenthetical group, or any primary operating variable which is a direct function of these quantities. Variants of Equation (3-3) have been used in application of inertial impaction theory to scrubber efficiency data, and Johnstone, Feild and Tassler (1954), assuming E_t was proportional to $(\Psi)^{1/2}$, correlated Venturi data by the relation:

$$E = 1 - \exp[-K(W/G)(\Psi)^{1/2}] \qquad (3\text{-}4)$$

where

(W/G) = liquid/gas ratio, gal./MCF

However, examination of the "straight-line" plots of F vs. $(W/G)(\Psi)^{1/2}$ shows that the experimental data collected by these authors do not quite follow the predicted line; the separate particle run series all show regular concave-upward curvature. Earlier, Johnstone and Roberts (1949) had correlated Venturi penetration data for dust collection, SO_2 absorption, and humidification on the basis of the specific drop area exposed per cubic foot of gas, without recourse to inertial impaction theory. Similarly inconsistent experimental data with respect to impaction theory are still being obtained; Boll (1971) found a fair fit of impaction theory to Venturi scrubbing data at low pressure drops of about 30" W.C., but virtually no correlation for higher ΔP operation.

One of the basic difficulties of Equation (3-1) is that it properly applies to uniform particle and drop sizes, and application to practical systems with a spectrum of sizes presents some difficulties. If the water drop size is taken to be uniform, then the overall efficiency is the summation of the target efficiency of each particle size multiplied by the fraction of the particles in that particular size range. If efficiency is defined as the weight fraction removed, E, then:

$$E = \int_{D_1}^{D_2} E_t (dM/dD_p)\, dD_p \qquad (3\text{-}5)$$

where (dM/dD_p) is the slope of the cumulative size distribution curve based on mass fraction analysis (Calvert and Taheri, 1966). While Equation (3-5) may account for particle size variation, it is valid only for a single water drop size, and the normal size distribution of water drops produced by spray nozzles, or by atomization within equipment presents a problem of extrapolation. In addition, there are fundamental difficulties deriving from target efficiency dependence on physical system properties which do not appear in Equation (3-1). Goldshmid and Calvert (1963) found that target efficiency was a function of the degree of mutual wetting (interfacial tension) of the aerosol and liquid pair. Further, wake capture behind the liquid drops was found to significantly increase the experimental target efficiencies at high air velocities and small particle sizes. High air velocities give rise to drop instability, and above approximately 200 ft/sec relative gas velocity, drops will oscillate and shatter. Drop atomization due to gas shear is usually handled by the Nukiyama and Tanasawa (1938) empirical correlation which, for the general case, may be stated as:

$$D_o = \frac{585(\sigma_L)^{1/2}}{\overline{V}_g(\rho_L)^{1/2}} + 597[\mu_L/(\sigma_L\rho_L)^{1/2}]^{0.45}(1000L/G)^{1.5} \qquad (3\text{-}6)$$

where

D_o = Sauter surface-to-volume mean diameter, microns

L/G = ratio of volume flow of liquid to volume flow of gas at vena contracta

$\overline{V}_g$ = relative gas velocity, meters/sec

σ_L = liquid surface tension, dynes/cm

μ_L = liquid viscosity, poises

ρ_L = liquid density, g/cc

The Nukiyama-Tanasawa equation has been one of the primary tools used in exploring the function of the high-energy loss Venturi scrubber which, like most wet scrubber units, was an empirical development for particulate-removal service. A good deal of attention has been devoted to exploration of the mechanics of particulate contact in the Venturi wet scrubber, and the derivation of Winklepleck (1970), introducing the pressure-loss term into equation (3-3) is of interest. The transfer of energy from gas to the liquid by frictional drag forces can be measured as the rate of gas pressure change with respect to time, and can be expressed in terms of a drag coefficient, C_f, so that

$$-dP/dt = \text{(Stokes' drag force)} \times \text{(droplet velocity relative to gas)} \times \text{(droplet concentration)}$$

$$-dP/dt = [(C_f/2g)(\pi D_g^2/4)(\rho_g \overline{V}_g^2)]\ (\overline{V}_g)(N_d) \quad (3\text{-}7)$$

Combining Equation (3-7) with (3-2) yields

$$-dN_p/N_p = \frac{-2E_{tg}}{C_f \rho_g \overline{V}_g^2}\, dP \quad (3\text{-}8)$$

Integration of Equation (3-8) with the boundary condition that at zero pressure drop the outlet particle concentration equals the inlet concentration yields:

$$\ln[(N_p)_{out}/(N_p)_{in}] = \frac{-2E_{tg}\Delta P}{C_f \rho_g \overline{V}_g^2} \quad (3\text{-}9)$$

Recognizing that the left-hand side of Equation (3-9) is simply ln(F), then

$$F = \exp(-2E_{tg}\ \Delta P/C_f \rho_g \overline{V}_g^2) \quad (3\text{-}10)$$

Thus, Equation (3-10) calls for a semi-log relationship between weight percent penetration and pressure drop, and the form of the equation is similar to the relationship of Equation (3-4) for the variable, (W/G). Just as appears to be the case for the actual experimental data on the effect of (W/G), the literature test data for the relationship between F and ΔP do not follow the indicated semi-log relationship. Detailed comparisons will be made in the next section of this report, but an examination of alternative theoretical bases is in order.

B. TURBULENT AGGLOMERATION THEORY

Contact between gas-suspended particles and/or drops can occur by various mechanisms other than simple ballistic impact induced by a large differential velocity. Ordinary Brownian motion can induce coagulation of particles, but it can be readily shown that the time and concentration requirements for a significant contribution from this source is outside the range covered by most wet scrubber applications. For the mechanisms of localized velocity gradient contacting prevalent in turbulent flow, the published viewpoints are conflicting. For example, Lancaster and Strauss (1971a) examine the case for the turbulent velocity gradient for a duct velocity of less than 40 ft/sec and conclude that turbulent agglomerative contact would not be significant as compared to Brownian coagulation. However, a few pages later, these same authors note the work of Levich (1962) to the effect that "the distortion of stream lines due to intense turbulence dominates the distortion due to inertial effects and ... each encounter based on straight line trajectories would be realized". There has been an almost intuitive recognition of this latter point on the part of a number of investigators of scrubber performance. For example, Kristal, Dennis and Silverman (1957) applied inertial impaction theory to their wet scrubber data, but qualified their approach by taking droplet projection velocities based on turbulent flow (despite a drop N_{Re} in the 35 to 335 range) citing Dalla Valle's statement (1948) "If the fluid is in turbulent motion, the motion of a particle injected into it will be turbulent regardless of the relative velocity between the particle and the fluid".

Despite the definite thread of intuitive acceptance of turbulent mixing as a primary contacting mechanism for wet scrubbers, no corresponding theoretical development has been applied to such equipment. The only turbulent contact theory for particle agglomeration in the literature appears to be that of Langstroth and Gillespie (1947) and this was derived for the case of self-agglomeration of smokes. Nevertheless, the development is believed of direct interest to wet scrubber data interpretation.

For the case of an aerosol suspended in turbulent air, Langstroth and Gillespie distinguish between the mass concentration, M_p, and the particle concentration, N_p, a distinction not directly made in inertial impaction theory. The rate of loss of mass to surfaces contacted is taken as proportional to the mass concentration, so that:

$$dM_p/dt = -\alpha\ M_p \qquad (3\text{-}11)$$

where α is the "mass loss constant". If α is independent of time, and if $M_p = (M_p)_o$ at $t = 0$, then

$$\ln[M_p/(M_p)_o] = -\alpha\ t \qquad (3\text{-}12)$$

The experimental data obtained validated Equation (3-12) and it should be noted that this equation states a semi-log relation between penetration and residence time. For a fixed time interval, mass penetration would be inversely proportional to the surface area available for contacting, and for the case of the wet scrubber where dispersed drops provide the surface loss area, the drop surface area per unit gas volume would be the primary variable, as was found by Johnstone and Roberts (1949) for their Venturi data.

If the number, rather than the mass of particles, is now considered, the change of a particle striking a surface is proportional to the number concentration, N_p, so that surface loss is

$$(dN_p/dt)_s = \beta\ N_p \qquad (3\text{-}13)$$

However, particle concentration can decrease by particle-particle collision as well as particle-surface collision, and since the rate of collision between two particles is proportional to N_p^2, the collision loss is

$$(dN_p/dt)_c = -kN_p^2 \qquad (3\text{-}14)$$

and the total rate of decrease of particle concentration is given by:

$$dN_p/dt = -(kN_p{}^2 + \beta N_p) \qquad (3\text{-}15)$$

Integration of Equation (3-15) yields

$$\ln(1/N_p + k/\beta) = \ln[1/(N_p)_o + k/\beta) + \beta t \qquad (3\text{-}16)$$

By making independent measurements of mass and particle number loss with time, Langstroth and Gillespie were able to evaluate the separate mass and number loss constants, α, β, and k, and determine their individual behavior with increasing air motion.

For a homogeneous aerosol, the ratio, (α/β) should be 1.0, while for aerosols having the usual particle size distribution, the ratio was found to be greater than 1.0. This was explained on the basis that the loss of the heavier particles was favored by the gravitational force which was operative over the appreciable time intervals employed, and by inertial forces resulting from turbulent deflection of the air currents at the collecting surface of the containing box. The relative importance of the agglomeration and surface loss mechanisms would be expected to depend strongly on the conditions used and the particle concentration. Inspection of the respective loss equations shows that for high particle number concentrations or high dust loadings, agglomeration which depends on $(N_p)^2$, would be favored, while the rate of surface loss, dependent on N_p, would dominate for relatively low dust loadings and/or heavier particles. For a scrubber or other particulate removal device, the surface loss or removal rate would be governed by the magnitude of the removal force designed into the unit: this is almost always an inertial removal force induced by deflection or reversal of gas flow, or by centrifugal action. On the other hand, for a wet scrubber the mechanism of particle growth to removal size would be both that of turbulent contact between dust and water drops, and dust-dust agglomeration. It is doubtful if the usual fixed-drop target efficiency impaction data is relevant to the random turbulent-contact case.

It is interesting to note that the recent theoretical work of Davis and Truitt (1971) along similar lines to those taken by Langstroth and Gillespie, very closely predicts the particle size distribution vs. time curves experimentally determined by these latter investigators, although no reference is made to this fact. The information contained in these studies of atmospheric aerosol removal phenomena has not been utilized in analyzing wet scrubber behavior, but would seem to offer a highly promising approach.

There is, at present, the inevitable number of contradictory statements concerning turbulent agglomeration which must be reconciled by further work. For example, Davis and Truitt state that "agglomeration by turbulence is predicted to occur at rates proportional to the cube of the particle diameter, hence larger particles are more subject to growth in a turbulent medium". This concept is in direct opposition to Equation (3-14) which states that collision growth is more likely for the smaller particles simply because there are a greater number of them.

In direct scrubber work, the observation that gas turbulence appeared to control the removal efficiency of wet scrubbers was made by Lapple and Kamack (1955) on the basis of extensive test work. This observation was later expanded by Semrau (1960) into the "contacting-power" concept, which states that the number of contacting transfer units is proportional to an exponential function of the total power input to the unit. Aside from the philosophical criticism that transfer unit theory should be properly applied only to a differential contacting unit, which wet scrubbers do not approximate, the use of contacting power represents a drastic oversimplification of the original Lapple and Kamack data. Further, the use of the contacting-power approach has not resulted in any ability to compare scrubber performance on either an absolute or relative basis, and the slopes of the log-log NTU vs. power input plots appear to vary randomly (Semrau, 1960). In fact, close examination of the original data used for such plots shows that the method of plotting often conceals significant and real relationships between omitted parameters and scrubber efficiency. However, the basic premise that turbulence is the primary mechanism of contact-removal is consistent with most data on scrubber performance, and the deficiency of the contacting power correlation lies in its form, not in its premise. A directed effort at further development of turbulent agglomeration mechanism elucidation and theory is obviously required; this approach appears to have been neglected because of the possibly premature acceptance of impaction theory as the valid theoretical framework.

C. SECONDARY COLLECTION FORCES

1. Diffusiophoresis and Thermophoresis

There are a number of fundamental physical processes which assist in driving a small particle toward a collecting surface, either drop or wall, but which are not generally considered as primary collection mechanisms. These include:

(a) Diffusiophoresis, also called sweep diffusion, or Stefan flow, which results from the flux of diffusing molecules under a concentration gradient. For example, when water vapor is condensing on a surface, the water molecules diffusing or sweeping toward that surface will tend to move particles along with them.

(b) Thermophoresis which results from the more rapid molecular motion at higher temperatures than at low, so that a particle in a temperture gradient is struck more frequently on the "hot" side and is driven toward the lower temperature level.

Diffusiophoresis and thermophoresis theory have been recently and thoroughly reviewed by Davis and Truitt (1971) and Lancaster and Strauss (1971a), and this material need not be repeated here. Attempts to employ diffusiophoresis as an auxiliary collecting mechanism usually involves steam injection coupled with subsequent condensation on a cold surface or water spray. Such a procedure not only involves diffusiophoresis, and thermophoresis as well, but direct condensation on at least a fraction of the particles, causing particle growth. The sharply-improved particulate collection efficiencies for certain humidification-quenching sequences must be attributed to condensation particle growth because the magnitude of the change is too large to be accounted for by the usual secondary collection mechanisms. Condensation is not truly a collection mechanism, but rather a particle-conditioning process, but the diffusiophoretic and thermophoretic effects are an inextricable part of any such vapor condensation operation.

2. Condensation-Conditioning

Fahnoe (1951), in one of the earliest studies of condensation effects, investigated the buildup of sodium chloride aerosol particles by steam condensation, and found that considerable size growth could be achieved. For both a cyclone scrubber and a Peabody impingement plate unit, it was determined that the overall collection efficiency of the aerosol increased from 40 to 90% for an injection rate of 0.01 lb steam/CF air processed. Surprisingly, it was found that only 10% of the steam condensed on the particles, with the remainder either condensing on the vessel walls or undergoing homogeneous nucleation. This distribution of the input steam raises a number of questions which, despite the recent research activity in this area, have not been satisfactorily answered. For example, the collection efficiency improvement has been attributed to the nucleation of the fog directly on the particulates, which is the usual meaning of particle growth. However, homogeneous nucleation would contribute an effective increase in particle population, and examination of the Langstroth-Gillespie statement of Equation (3-14) certainly indicates that the incremental particle concentration would be an additive effect. While all other effects of steam condensation have been considered and investigated in recent investigations, the "population explosion" caused by homogeneous nucleation of fog particles has not been examined.

Recent work by Lancaster and Strauss (1971b) on the effect of steam injection in wet scrubbers showed that the improvement in scrubber performance was determined by the quantity of steam injected, and not by the quantity condensed on the particles. This is in direct contrast to the careful experimental work of Davis and Truitt (1971) on a simple condensation tube, who found that particle removal was proportional to the steam condensation rate. Davis and Truitt further found a marked difference in particle growth behavior between hydrophilic and hydrophobic aerosol particles. In a condensation field, hydrophilic and hygroscopic particles all showed fairly uniform growth; conversely, the hydrophobic particles showed massive growth for only a small fraction of the total particles, with the remainder showing no growth at all. The simplicity of the test equipment allowed a distinction to be made between growth and removal processes, and perhaps the most important finding of this work was that the gas Reynolds number was a determinant of the efficiency of removal, and this effect was attributed directly to turbulent agglomeration.

IV. WET SCRUBBERS: DESIGN FOR PARTICULATE REMOVAL

A. CONTROLLING PARAMETERS

The variables governing wet scrubber performance for particulate removal have been investigated by Lapple and Kamack (1955), Johnson et al (1955), Kristal, Dennis and Silverman (1957), Brink and Contant (1958), Silverman and Davidson (1956), and Ingels, Shaffer and Danielson (1960). Most recently, Calvert and Legatski (1970) reported on an extensive investigation of seven commercial types of wet scrubbers, and Lancaster and Strauss (1971) presented data on the effects of steam injection on collection efficiency. Although these investigations covered a wide variety of wet scrubbing equipment, both low and high-energy types, there appears to be general, if not universal, agreement that there are three primary variables governing performance:

(a) Inlet dust loading

(b) Water/Gas Ratio

(c) Gas pressure drop and/or gas velocity

Most of the cited literature presents performance correlations in terms of efficiency of removal as functions of each separate primary variable, although in many instances, maintenance of constancy of the other two primary variables is not followed. In addition to the three primary variables indicated above, data are occasionally provided on the effects of a group of secondary variables, including:

(a) Inlet dust particle size and distribution

(b) Scrubber type

(c) Water droplet size and injection velocity

(d) Nozzle location

In all cases of dispersed-liquid capture of particulates, examination of the experimental performance data shows that, for a given dust and given set of secondary variables, it is possible to completely describe the efficiency of a scrubber solely on the basis of the three primary variables. Failure to recognize this fundamental relationship may give rise to a considerable degree of misinterpretation of data and invalid conclusions concerning relative unit performance. In fact, the present absence of a useful basis for comparison of equipment performance may be attributed to this failure, and one of the primary objectives of this data review is to remedy this deficiency.

B. INLET DUST LOADING

The inlet dust loading variable has the distinction of being ignored in most theoretical inertial impaction treatments of the scrubbing mechanism, but requiring almost immediate experimental attention in actual test work because of its dominant effect. Even after its laboratory or test identification as a primary, if not controlling variable, it may later be overlooked in secondary efforts at correlation. For example, in the work of Lapple and Kamack (1955) on several types of scrubbers, the inlet dust loading was the initial parameter investigated, and because of its profound influence on wet scrubber efficiency, all subsequent data were corrected to an arbitrary reference dust loading of 8 gr/CF. This article initially suggested the contacting-power concept for estimating efficiency (at an implied constant inlet dust loading concentration) but the stated important qualification of correcting to a single reference feed concentration has been de-emphasized or overlooked in all later work on this concept.

Johnson (1955) tested both a wet cyclone scrubber and a dynamic wet scrubber (Hydro Volute) and determined that, for both devices, there was a direct relationship between weight efficiency and dust loading. For the dynamic scrubber, an increase in fly ash loading from 0.1 to 10 gr/CF air gave an overall efficiency increase from 94.6% to 98.2%. Similar behavior was observed for the cyclone, operated both dry and wet, and after noting the importance of dust concentration on the separation efficiency of inertial collectors, Johnson advanced the explanation that "inertial collectors tend to concentrate the dust as a first step in the separation process and this affords an opportunity (by crowding the particles together) for agglomeration".

Kristal (1957) tested a Solivore scrubber (low-energy multi-Venturi unit) and found that for "finer aerosols", such as $CaCO_3$, the increase in collection efficiency with increased dust loading was significant. As will be shown below, the apparent size distinction in dust behavior was the result of an initial dispersal problem in the feed unit, rather than a real parameter, and with allowance for this dispersion effect, all efficiency data consistently showed the loading dependency. The effect of dust loading was explained on the basis of agglomeration: "increased retention with higher dust loadings is probably due to the greater opportunity for agglomeration as a result of higher particle concentration".

It is interesting that neither Kristal nor Johnson examined the fundamental anomaly inherent in their explanations. Assuming the correctness of their statements that higher inlet dust loadings yield higher agglomeration rates, why should this yield greater percentage efficiencies based on gross inlet dust concentrations? If agglomeration rates are simply proportional to inlet dust concentrations, then greater percentage removal at higher inlet dust loadings would require longer scrubber residence times as well, which is not consistent with the generally constant gas flow conditions employed for these tests. If equipment residence time remains constant, the only apparent way that percentage efficiency would increase with inlet gross weight dust concentration is for the agglomeration rate to be more than simply proportional to dust loadings. In order for a power or exponential function dependency of agglomeration rate on gross weight dust loading to prevail in a dispersed-water contactor, then multi-body collisions (three or more) between dust-dust and water-dust particles would have to be dominant. Additionally, if this mechanistic explanation is correct, then there probably should be a minimum dust concentration above which the efficiency-dust loading dependency would be observed. This possibility and the nature of the dust-loading effect can best be explored by examining in detail some of the relevant literature work.

1. Data of Ingels, Shaffer and Danielson (1960)

Perhaps the most interesting data on the effect of inlet dust loading and water/gas ratio on scrubber performance is the commercial test data presented in Chapter 7 of Danielson (1967). These data were taken from the original study by Ingels (1960) on multi-stage centrifugal spray scrubbers and baffled tower spray scrubbers in service on hot-mix asphalt paving batch plants. Danielson indicates that the significant dust variable is the minus 200-mesh fines feed rate to the dryer, and it is necessary to refer to the original 1960 study to determine the derivation of this statement.

The original article states that the primary dust variable governing scrubber efficiency was the absolute scrubber inlet dust loading in lb/hr, with higher efficiency being obtained at higher absolute dust loadings. The scrubbers were preceded by cyclone pre-cleaners, and it was noted that "scrubber efficiency was so dependent on the degree of pre-cleaning that the effect of other variables on collection efficiency was completely masked in the available data". This effect was graphically shown by Ingels as Figure 4-1, a plot of scrubber efficiency vs. absolute dust loading. Absolute dust loadings were used despite the fact that gas flow rates for the plotted test data ranged from 16,100 to 28,300 SCFM, which would certainly yield different relative inlet dust loading concentration values. In reviewing these data, Friedrich (1969) calculated and tabulated the inlet dust loading concentrations, in gr/CF, utilizing the flow rates and the absolute emission data, but limited his comment to noting the wide variations in scrubber inlet loadings and the absence of information on the design of the primary collectors operating as pre-cleaners.

Figure 4-1, as presented by Ingels, strongly resembles a standard grade-efficiency curve, with an almost vertical rise in efficiency from less than 85% at loadings of 100 lb/hr to over 95% at 300 lb/hr. Further increases in loadings from 1000 to 3000 lb/hr show only a gradual efficiency increase from 97% to 99+%. This plot does not reveal any basic efficiency difference due to scrubber type, or nature of fuel used in the dryer, but the extreme sensitivity of efficiency to dust loading in the range below 400 lb/hr is very apparent. Utilizing the inlet dust loading tabulations of Friedrich (1969) for the Ingels' data, the data of Figure 4-1 were re-plotted in terms of weight per cent penetration vs. inlet dust loadings in gr/CF as a log-log plot in Figure 4-2. Tabulated values for these runs are also presented in Table 4-1, and the penetration correlation approach was chosen because of the obvious lack of efficiency sensitivity in Figure 4-1 at the higher efficiency levels.

Despite the point scatter in Figure 4-2, which is not unexpected in view of the extreme variation in the other parameters (water/gas ratio, gas flow rate, scrubber type, dryer fuel), the data appear to follow a straight line of slope = -1. This indicates the penetration to be inversely proportional to inlet dust concentration, which is not at all evident in Ingels' absolute dust-loading plot, Figure 4-1. This finding of an inverse proportionality between penetration

FIGURE 4-1

WET SCRUBBER EFFICIENCY ASPHALTIC CONCRETE PLANT DUST DATA OF INGELS, ET AL (1960)

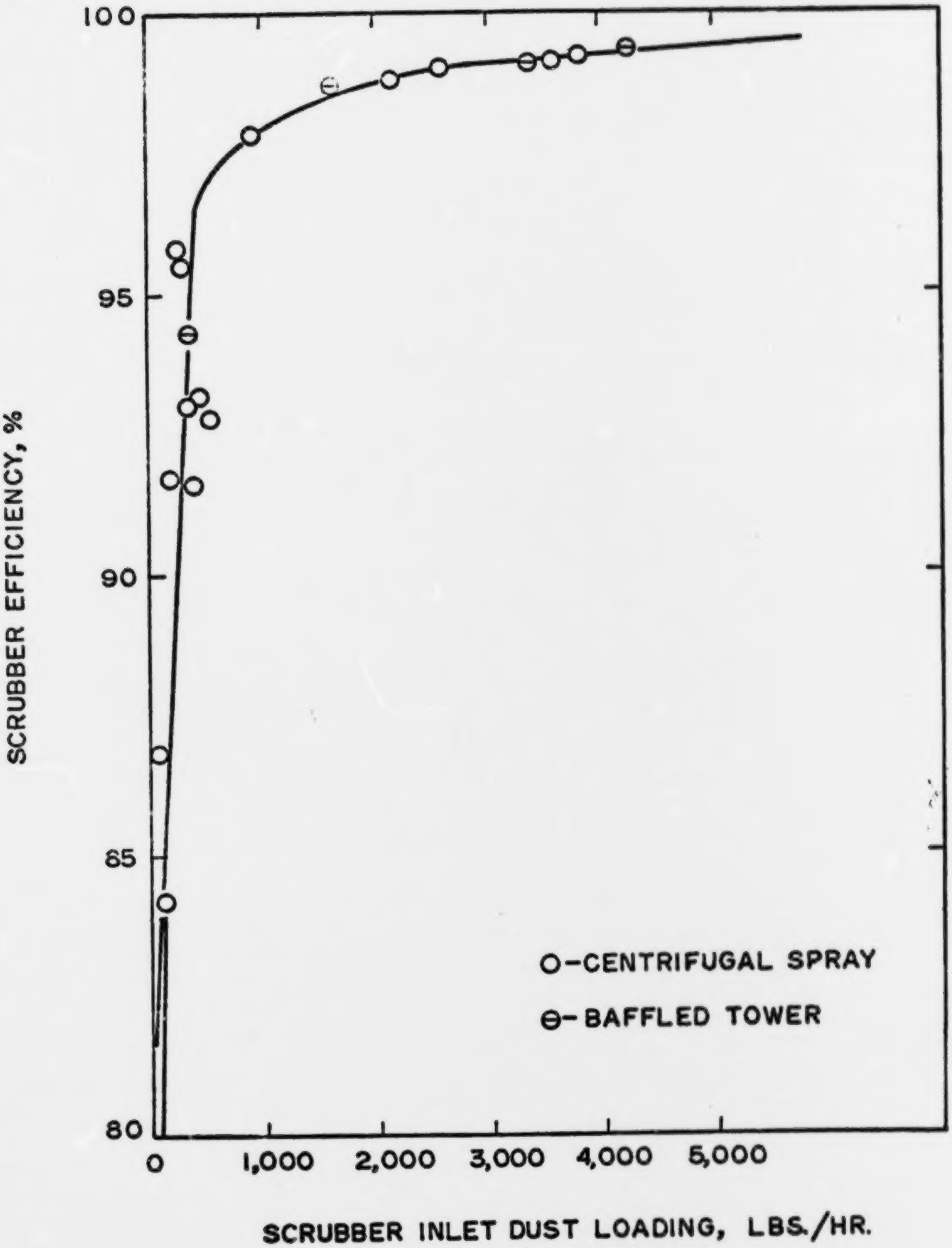


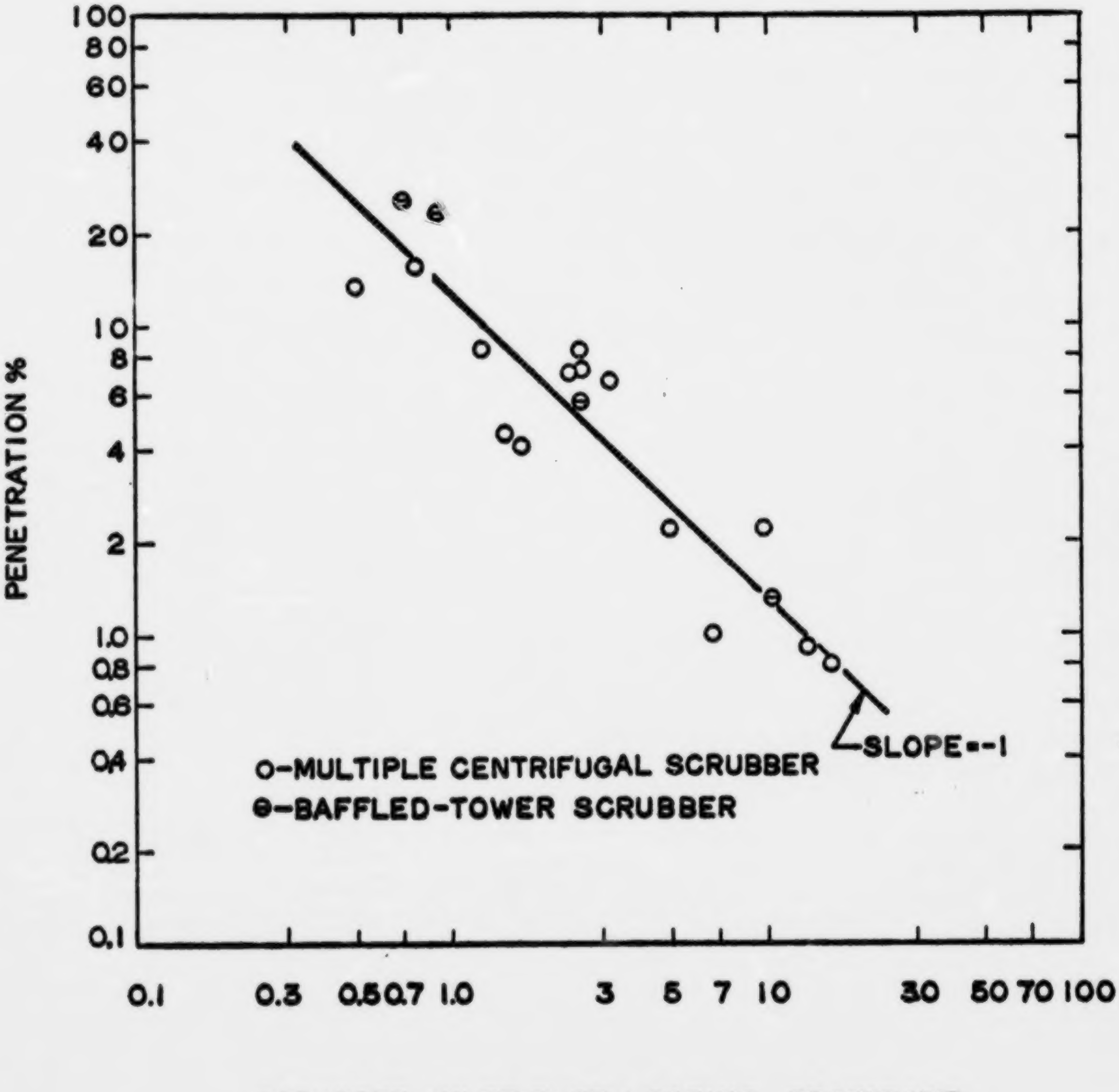
TABLE 4-1

TEST DATA FROM ASPHALTIC CONCRETE PLANTS CONTROLLED BY SCRUBBERS

DATA OF INGELS (1960)

Test No.	Inlet Dust Loading, gr./CF	Penetration %	(W/G) gal/MCF	$(C_d)(W/G)$	Fuel
(a) Multiple Centrifugal-Type Spray Chambers					
C-357	4.95	2.2	6.62	32.7	Oil
C-82	2.51	8.4	3.94	9.9	Oil
C-379	18.3	0.9	6.38	116.8	Oil
C-355	9.84	2.2	6.81	67.0	Oil
C-372B	0.773	15.8	10.99	8.5	Oil
C-372A	0.492	13.2	11.11	5.46	Gas
C-369	2.32	7.0	5.41	12.55	Oil
C-379	15.85	0.8	5.92	93.8	Gas
C-337	1.46	4.5	11.11	16.2	Oil
C-426	6.7	1.0	7.75	51.9	Oil
C-417	2.56	7.2	2.94	7.53	Oil
C-425	3.14	6.8	4.26	13.4	Oil
C-385	1.24	8.3	4.56	5.65	Oil
C-433	1.58	4.2	8.12	12.8	Gas
(b) Baffled Tower Scrubbers					
C-393	25.5	0.7	12.01	306	Oil
C-185	10.2	1.3	19.40	198	Oil
C-234	2.52	5.7	5.70	14.4	Gas
C-418	23.2	0.9	8.90	208	Oil

FIGURE 4-2
PENETRATION AS FUNCTION OF SCRUBBER INLET DUST LOADING DATA OF INGELS (1960) HOT-MIX ASPHALT PAVING PLANTS



and inlet gross loading is, of course, highly unusual not only in itself, but also because of the lack of any prior indication of such a relationship in any series of scrubber tests or for any piece of scrubber equipment. If it could be generalized or proven valid, it would have extreme significance for correlating wet scrubber performance and rationalizing test methods. As will be shown below, re-examination of the literature data indicate that, when allowance is made for feed dispersion variables, this relationship does hold true for most reported wet scrubber test data.

In this particular case, as is true of most field test data, inlet dust particle size distribution is also a variable, and this complicates validation of Figure 4-2 data. The only information provided by Ingels on this latter variable is that of Table 4-2, and these data raise a number of basic questions. In order to get to the effect of the secondary variables on efficiency, Ingels avoided the inlet dust loading "masking" effect with the argument that "the fractional collection efficiency of particles larger than 10 microns (in the scrubber) proved to be 99.7 percent. Consequently, the variables and operating conditions which affect the amount and collection efficiency of the 0 to 10 micron fraction should be reflected in the absolute stack emissions". All of the data presented in Danielson (1967) on these scrubbers were derived on this basis. However, Ingels' particle size analysis of Table 4-2 not only do not support this argument, but lead to the opposite conclusion. Ignoring the agglomerated 44+ micron sample data, it is clear from Table 4-2 that only in Test Series C-393 is the collection efficiency of the plus 10-micron dust above the stated 99.7 percent level. In Test Series C-369, C-372A, C-372B and C-422(1), the 10 to 44-micron fraction collection efficiencies are considerably less than 99 percent.

With respect to the plus 44-micron fraction, which shows an anomalously lower fractional efficiency than was obtained for the smaller dust size fractions, it was established by microscopic observations that this fraction consisted of wetted, agglomerated fines. Curiously, the one set of test data in Table 4-1 that shows no agglomerated fines in the 44+ micron fraction of the scrubber outlet, C-393, is for the baffled tower scrubber; all of the other tests in Table 4-2 are for multiple centrifugal spray chambers. While this evidence is rather thin, the possibility arises that the wetted fines and agglomerates are more effectively removed in a baffled unit than in a centrifugal spray chamber.

TABLE 4-2

FRACTIONAL COLLECTION EFFICIENCY DATA FOR SCRUBBERS SERVING ASPHALTIC CONCRETE PLANTS

DATA OF INGELS (1960)

Dust Particle Size, Microns	Inlet, %	Outlet, %	Efficiency, %	Inlet, %	Outlet, %	Efficiency, %
	Test Report Series, C-393			Test Report Series, C-369		
0-10	13.0	99.3	95.2	76.4	79.9	92.8
10-20	71.1	0.0	100.0	6.3	3.8	96.0
20-44	9.6	0.0	100.0	2.8	2.0	95.0
44+	6.3	0.7	99.3	14.5	14.3[a]	93.1
	Test Report Series, C-372A			Test Report Series, C-372B		
0-10	78.0	83.0	85.0	91.0	82.0	85.7
10-20	18.0	5.0	96.2	9.0	3.0	99.4
20-44	2.0	1.0	93.3	0.0	2.0	---
44+	2.0	11.0[a]	26.5	0.0	13.0[a]	---
	Test Report Series, C-422(1)					
0-10	80.4	73.2	---			
10-20	18.6	5.1	---			
20-44	1.0	4.5	---			
44+	0.0	17.2	---			

[a] Microscopic examination indicated that the outlet samples were agglomerated.

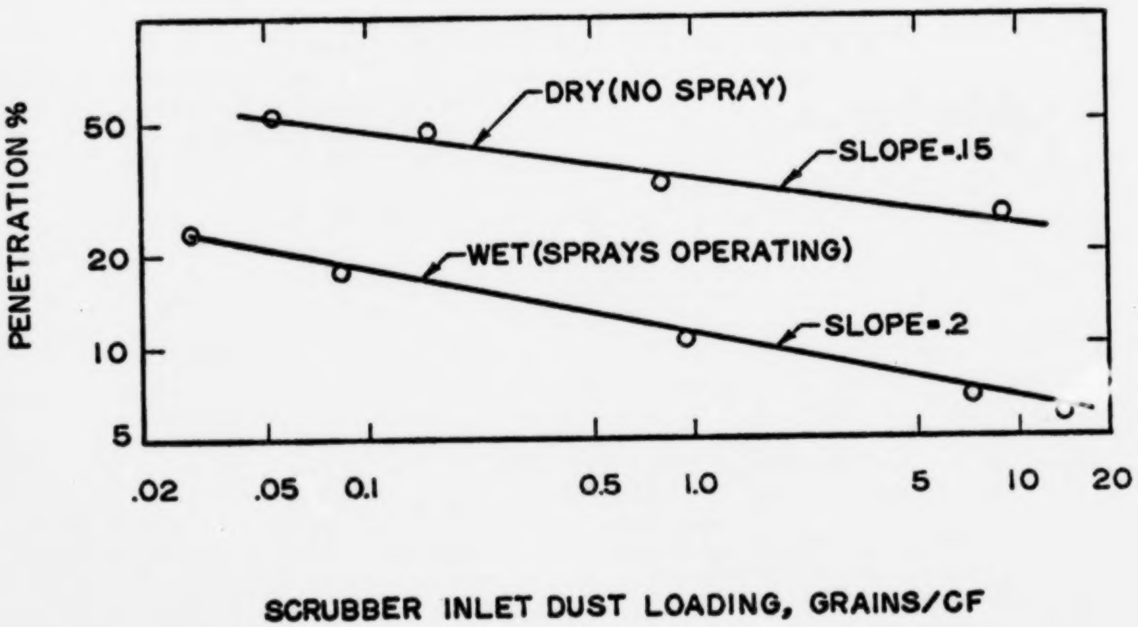
Conversely, Ingels found that the centrifugal spray chamber was about 5.0 lb/hr more effective than the baffled tower in reducing the absolute stack emission. This seeming contradiction may be resolved if it is assumed that the wetting (agglomerate-formation) and removal functions of a wet scrubber are consecutive and independent. Thus, the data would indicate that the centrifugal spray units employed are more efficient in contacting the dust particles with water, but less effective than the baffled units in removing all of the wetted material prior to exhaust. The view of a dispersed-liquid scrubber as a dual-functional device involving consecutive stages of agglomerate-formation and agglomerate-removal, with separate and characteristic stage efficiencies, may serve to rationally differentiate equipment performance.

2. Data of Johnson et al (1955)

Johnson's data on the penetration-dust loading relationship for both dry and wet runs on a cyclone scrubber operating on micronized talc (mass median diameter = 1.4 microns) are presented in Figure 4-3. Again, an inverse relationship between penetration and dust loading is shown (for both dry and wet operation), but the slope of the line for wet operation is -0.20, which is considerably less than the -1.0 indicated by Ingels' industrial data, and shows a fractional exponential effect of dust loading, C_d, on penetration. It is important to note that the "Harvard generator" was used in these runs (First, 1953); the test dust is injected into the system through a dispersing Venturi after being aspirated off a turntable. If agglomeration effects are important, as Figure 4-3 certainly indicates by the fact that dry penetration is an inverse function of dust loading, then it would seem to be necessary to either check out the test dust for complete dispersion, and the absence of pre-existing agglomerates in the feed, or to ensure their removal by pre-cycloning (as per Ingels' data). An inspection of the test system diagram and sampling methods shows that no precautions were taken against this eventuality, and further, no particle size distribution data on feed samples are provided. In view of the data of Figure 4-3, showing the relative ease of self-agglomeration of the dry talc in a cyclone, the use of another collection device, the Venturi, as a dispenser in this case does not appear logical, and it is highly likely that incomplete dispersion, or secondary agglomeration, was prevalent.

FIGURE 4-3

PENETRATION DIFFERENCE FOR DRY vs WET CYCLONE OPERATION AS FUNCTION OF INLET DUST LOADING DATA OF JOHNSON (1955)



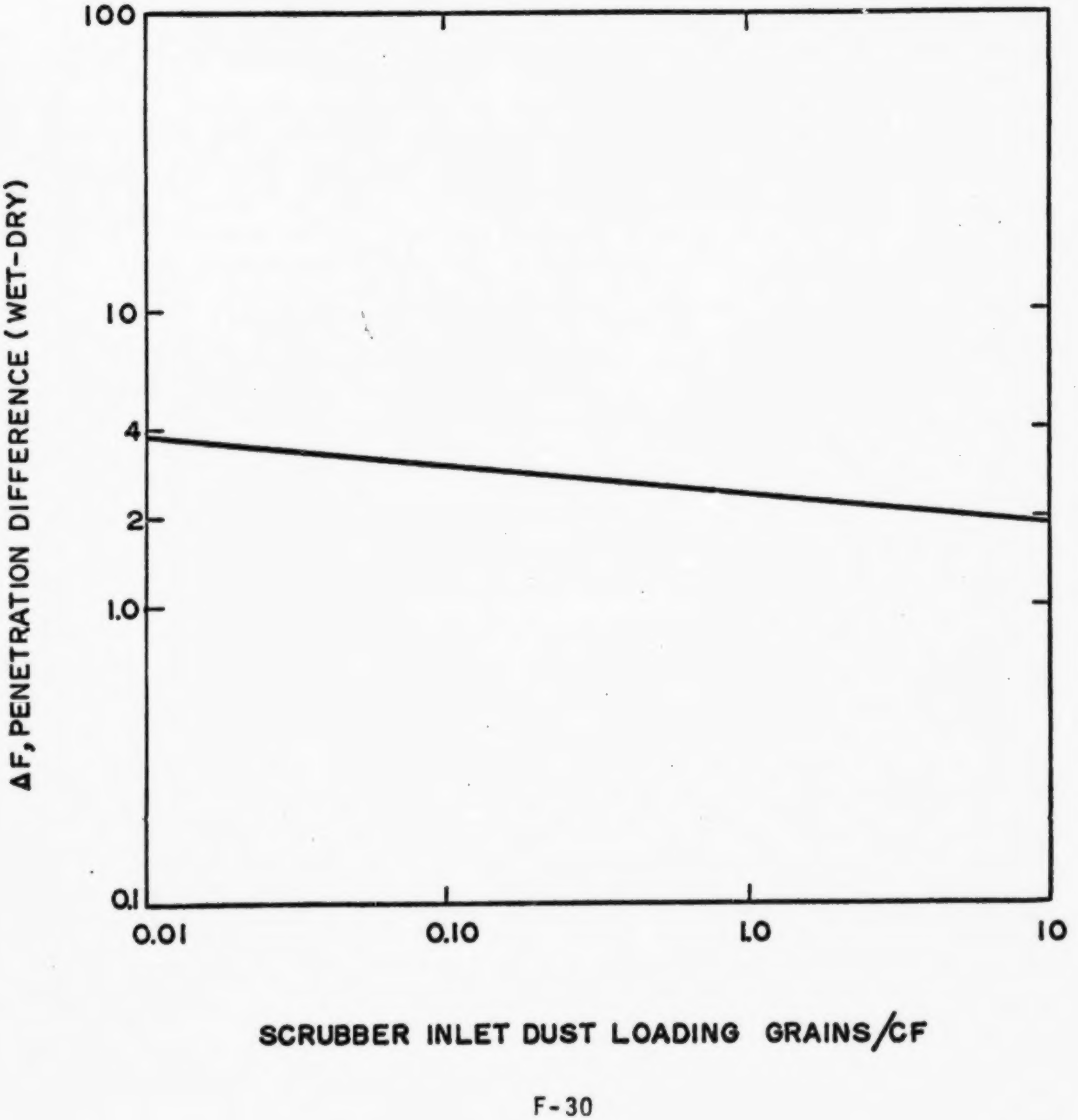
The use of a Venturi as a feed dust dispersing device is not confined to the Johnson work. The same device was used by Lapple and Kamack (1955) and by Kristal et al (1957), and as will be shown below, similar "anomalous" results were obtained by these investigators for those dusts which may have had a self-agglomeration tendency. If non-dispersal or pre-agglomeration of feed dust occurs upstream of the contacting device on test, then one result would be a flattening of the penetration vs. dust concentration line, and the comparative experimental data are consistent with this possibility. The use of a wet-collector device as a dry feed dust disperser should properly be viewed with suspicion in the absence of verifying size distribution data.

In noting that the slope of the dry-operation line on Figure 4-3 was -0.15, as compared to -0.20 for the wet-operation line, Johnson assumed that the effect for the dry line was dust-dust agglomeration, and concluded that "some other effect than agglomeration of dust is contributing to increased efficiency when water is sprayed. The greater rise in efficiency with loading (under wet conditions) is a result of an increase in the relative number of collisions between particles and droplets". It is apparent that "agglomeration" is being implicitly defined solely as dust-dust collisions, and that water-dust collisions give rise to "some other effect". There would appear to be a needless semantic distinction here between the types of multi-body collisions leading to particle growth. If a certain particle mass is required prior to wall-collection by the inertial cyclone forces, then the degree of removal for any given mode of operation will not be a function of whether this critical size is attained by dust-dust self-agglomeration or dust-water inter-agglomeration.

Some additional insight into the probable mechanisms at work in Johnson's experimental work can be obtained by plotting the difference in wet and dry penetration, ΔF, of Figure 4-3 against dust concentration, as in Figure 4-4. The slope of the ΔF vs. C_d line in Figure 4-4 is -0.10, indicating a slight decrease in the relative effectiveness of wet operation from $\Delta F = 37\%$ at 0.01 gr/CF to $\Delta F = 18\%$ at 10 gr/CF. This would be expected on the basis that self-agglomeration of the dust is already at an appreciable level at high dust concentrations and the addition of more particles (droplets) would not have as large a relative effect as when dry particle concentration is too low to yield appreciable self-agglomeration. However, the relatively small 50% decrease in ΔF over a 1000-fold range of loading

FIGURE 4-4

PENETRATION DIFFERENCE FOR DRY vs WET CYCLONE OPERATION AS FUNCTION OF INLET DUST LOADING DATA OF JOHNSON (1955)



values from 0.01 to 10 gr/CF in Figure 4-4 indicates a probably dominant effect of water droplet concentration in the wet agglomeration runs. The use of 400 psi hydraulic nozzles at a flow rate of 6 gal/MCF air probably accounts for this effect, and this raises the question as to whether the effect of the dust loading concentration variable should be considered alone or in conjunction with the water droplet concentration. If the turbulent agglomeration-collision mechanism is the means by which the dust particles grow to a critical collection size, then it would appear that collection efficiency under a given force field would be determined by the product of the dust and water particle concentrations. Before examining the data on this basis, it is worth briefly noting some of the additional literature evidence on the effect of the water droplet concentration on collection efficiency.

C. WATER/GAS RATIO

A correlation approach using water droplet concentration as a prime variable has firm precedence in both theory and data in wet scrubber performance analysis. For example, Kristal (1957), in reporting the results for the number of spray stages in multi-stage low-energy Venturi scrubbers, found that particulate-removal efficiency was dependent on the spray rate, and concluded that the concentration of water drops (in the contact zone) was an important factor. In fact, Kristal stated that "all tests showed an inverse relationship between per cent passage and water rate within the range tested". As an incidental observation, it should be noted that this relationship is not consistent with impaction theory which calls for an exponential (semi-log straight line plot) relationship between penetration and (W/G) ratios.

Ingels (1960) presented data on the effect of water/gas ratio for multiple centrifugal and baffled tower scrubbers, showing that increasing (W/G) reduced the absolute stack emissions. It was observed that low (W/G) ratios were more than proportionately less effective than higher ratios. This nonlinearity of the (W/G) effect on efficiency was not investigated further, although the spacing of the constant (W/G) lines on Ingels' efficiency plot suggest a logarithmic progression from low to high (W/G). The use of (W/G) ratios, usually expressed as gallons/1000 cubic feet of gas flow, is generally assumed to be a relative measure of the water droplet concentration for a given test unit, although this is not strictly true for all water injection means. However, for most injection systems which depend on gas turbulence-induced liquid dispersion, or where the (W/G) ratio varies by reason of the change in gas flow at constant liquid injection rate, as in Ingels' data, the droplet concentration should be directly proportional to (W/G).

Lapple and Kamack (1955) presented data on pressure drop as a function of (W/G) for several test scrubbers, but peculiarly, did not make similar presentations for dust penetration as a function of this variable, although such determinations were made. Instead, penetrations were plotted as functions of inlet dust loading, with (W/G), as a secondary "floading" parameter. Inspection of these latter plots show that, at constant dust loading, penetration decreased with increasing (W/G), although the data are too limited to attempt cross-plots.

In Johnson's data (1955), the maximum efficiency levels were obtained in a wet cyclone scrubber with the highest spray nozzle atomization pressure of 400 psig, and the efficiency levels at lower pressures were observed to be roughly proportional to the nozzle pressure. Also, for a given nozzle pressure, the collection efficiency was a linear function of cyclone inlet gas velocity, except for the extremely high 400 psig nozzle pressure run. These data indicate both the effect of water droplet concentration and turbulent gas mixing on collection efficiency. Unfortunately, the pre-agglomeration of the feed dust compromises the results, and it is questionable if the data can be used for more than qualitative behavior comparison.

Review and re-plotting of the data covered by the above investigations definitely established that the combined dust and water particle concentration terms, expressed as a product, $(C_d)(W/G)$, served to correlate the effect of these two primary variables on the efficiency. This correlating parameter has been termed the "agglomeration index", and its utility is explored below.

D. AGGLOMERATION INDEX

Particle growth to a critical minimum size necessary for removal from the gas phase by inertial wall collection or other mechanisms may be considered to occur primarily by dust-water collisions, and the two usual test variables, inlet dust loading and water/gas ratio, can be taken as (approximate) particle concentration terms. A theoretically-correct expression for collision probability would involve the product: (No. dust particles/CF) (No. water drops/CF). Expressing dust loadings and water/gas rates as number concentrations would require correcting the mass or volumetric concentrations for the cube of the mean particle diameter, the further correction of the dust loading for solids density. However, for a given test dust and water-injection system, the usual respective (C_d) and (W/G) units of grains/CF and gallons/MCF may be used directly in the form of an "agglomeration index", X_c, such that:

$$X_c = (C_d)(W/G) \qquad (4\text{-}1)$$

where C_d = dust concentration/unit gas volume, commonly gr/CF

W/G = water/gas volumetric ratio, commonly gal/MCF

Underlying the postulation of Equation (4-1) are several general assumptions. It is assumed that the primary water-dust contacting mechanism is turbulent mixing, in agreement with the work of Semrau (1958), and that such contacting will be a statistically random process. It is further assumed that the water drops are larger than the dust particles and above the critical collection size, while the dust will be below this size. This will be true in most wet scrubbing units, and therefore the dust-dust collision processes may be ignored. However, as already seen, if critical-size dust pre-agglomerates exist in the feed, different behavior may be expected than for well-dispersed dusts. Because the primary mixing mechanism is turbulence, the agglomeration index can only be used as a correlating parameter at constant levels of turbulence scale and intensity. For a given scrubbing unit, this implies the proper application of the X_c parameter at constant gas velocity and/or pressure drop. Another reason for specification of constant gas velocity for use of the X_c parameter is the interaction between gas velocity and water drop stability. Above a certain range of air velocities, roughly 200 ft/sec, drop-shattering predominates, and drop size is a function of the gas velocity. In this context, Equation (4-1) is only a partial index of collision probability, and a gas turbulence or velocity function term would be required for complete description of the correlating parameter. This final variable will be covered in a later section of this report. However, in order to test X_c within the limitations outlined, it is informative to return to the data of Ingels (1960) to test the applicability of this approach.

1. Data of Ingels (1960)

Values of $(C_d)(W/G)$ were calculated for Ingels' industrial test data, and are included in Table 4-1. When the table 4-1 data are now plotted as per cent penetration vs. the agglomeration index, X_c, as in Figures 4-5, 4-6 and 4-7, separation of the test data on the basis of dryer fuel and scrubber type is obtained. While Figure 4-5 still exhibits point scatter, the best line through the data for the multistage centrifugal scrubbers (oil-fired dryer) gives the same -1.0 slope shown in Figure 4-2, where penetration was plotted against inlet dust concentration alone. Figure 4-6, a similar plot for the baffled-tower, gas-fired scrubbers, shows that these points fall parallel to, but lower than, the line for the centrifugal scrubbers, oil-fired. The higher penetration shown for the baffled-tower scrubbers compared to the centrifugal spray scrubbers is in accordance with the findings of Ingels (on the basis of absolute stack emissions and a curvilinear multiple correlation) that the latter type of scrubber is the more efficient in this instance.

Figure 4-7 compares the gas-fired dryer data for the two types of scrubbers with the lines for the oil-fired units, established in Figures 4-5 and 4-6. Although the data are quite limited, penetration for the gas points appear to be less than for oil-firing, especially for the baffled-tower equipment (one point). Again, this is in agreement with the conclusions of Ingels, based on his entirely different correlation approach, that stack emissions were higher when the dryer was oil-fired, probably due to additional particulate matter contributed by the fuel oil. It should be noted that, while point scatter may impair the validity of the conclusions drawn from the plotted data, Ingels also stated that the data scattered badly, "even when corrected for the variables studied".

The fact that the use of the $(C_d)(W/G)$ correlation group allows separation of the fuel and scrubber type variables in Ingels' data is an indication of the potential utility of this approach. Essentially, the same set of conclusions may be derived from the simple penetration vs. X_c plots as was obtained by Ingels by statistical analysis of the same experimental data. Further generalization of this correlation technique requires additional data review, and a comprehensive series of wet scrubber test data has recently been provided by Calvert and Legatski (1970). These data allow a remarkable demonstration of the utility of the agglomeration index approach to comparative scrubber evaluation.

FIGURE 4-5

PENETRATION AS FUNCTION OF AGGLOMERATION INDEX, (C_d) (W/G)

DATA OF INGELS (1960)
MULTIPLE CENTRIFUGAL SCRUBBERS
OIL-FIRED DRYER

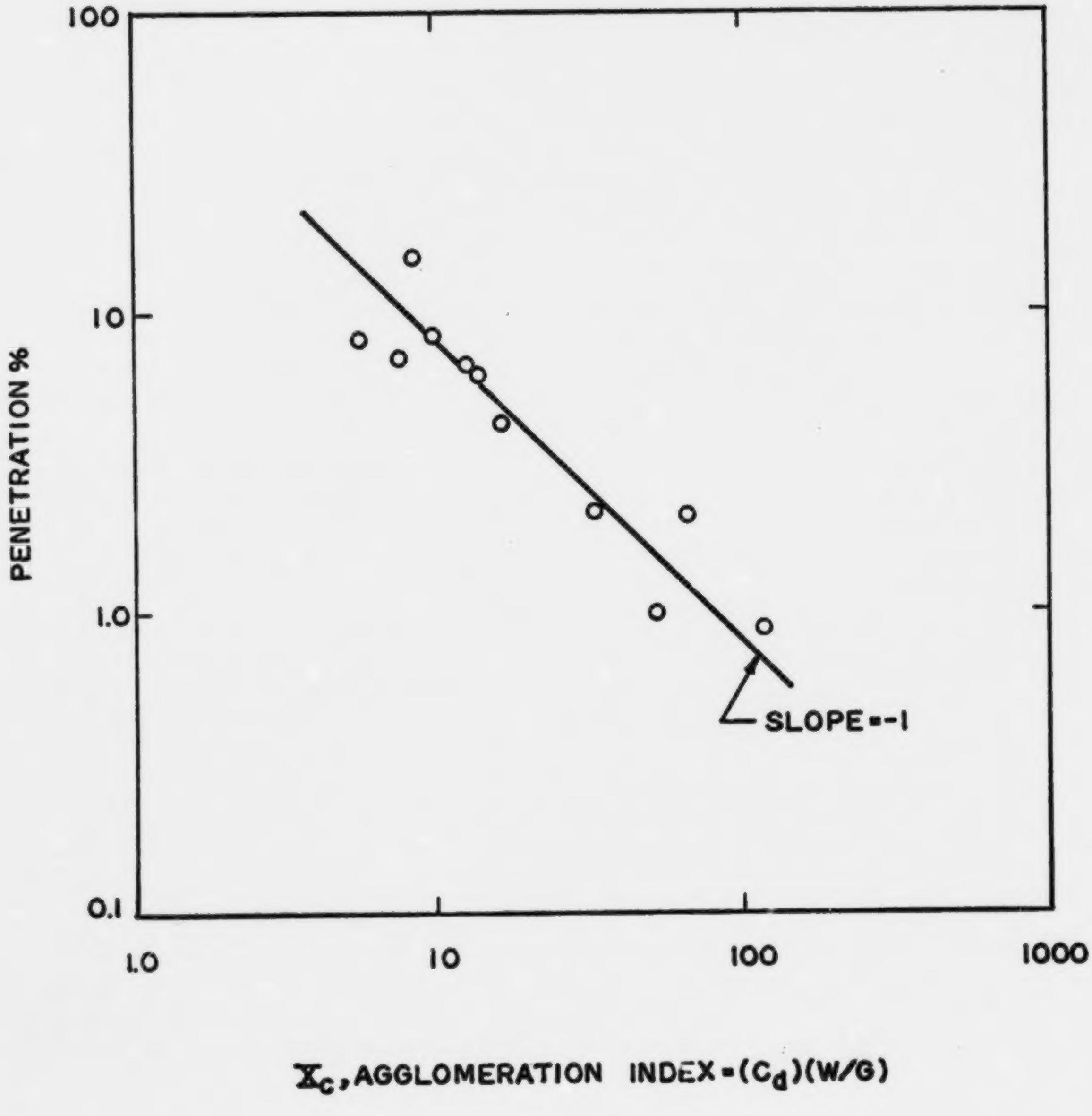


FIGURE 4-6

PENETRATION AS FUNCTION OF AGGLOMERATION PARAMETER, $(C_d)(W/G)$

DATA OF INGELS (1960)
MULTIPLE CENTRIFUGAL SCRUBBERS
GAS-FIRED DRYER

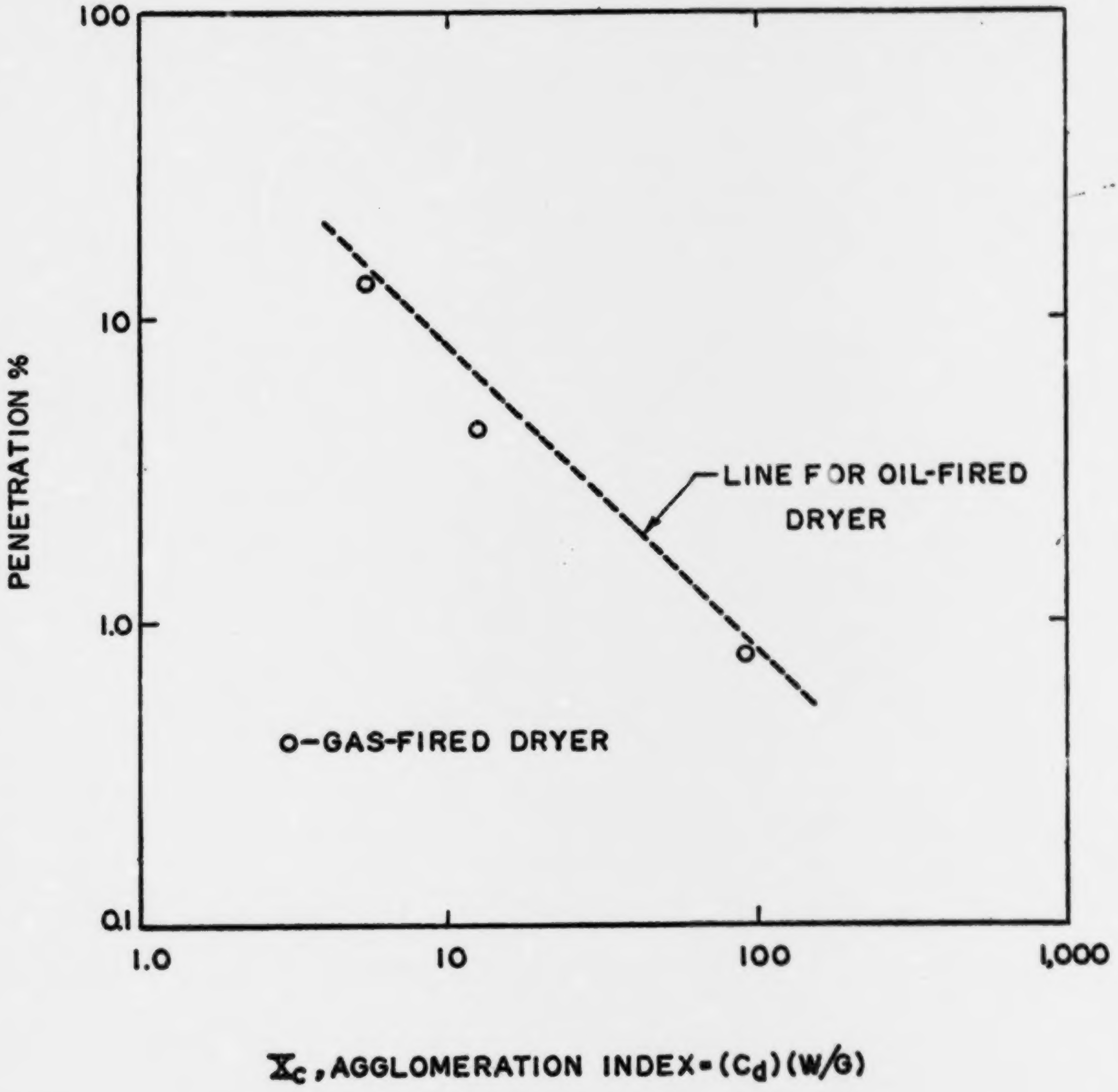
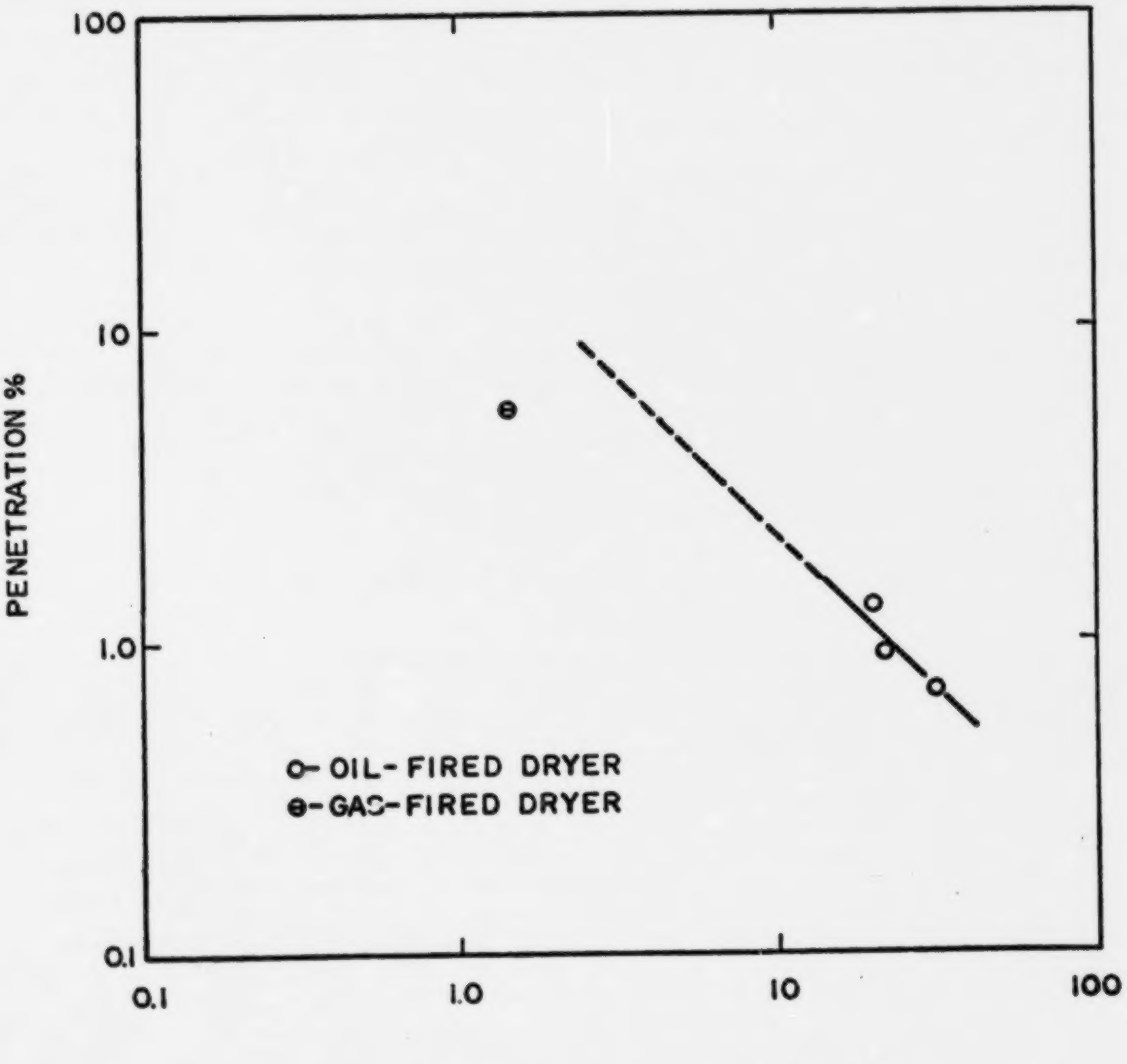


FIGURE 4-7
PENETRATION AS FUNCTION OF AGGLOMERATION INDEX, (C_d) (W/G)
DATA OF INGELS (1960)
BAFFLED TOWER SCRUBBERS



X_c, AGGLOMERATION INDEX = (C_d)(W/G)

2. Data of Calvert and Legatski (1970)

This investigation covered the experimental performance, in terms of penetration, of a series of wet scrubbers tested against relatively low concentrations of respirable coal dust. The scrubbers tested included:

(1) Venturi

(2) "Ventri-Rod"

(3) "Ventri-Sphere"

(4) Impingement Plate

(5) "Air Tumbler"

(6) Packed Bed

(7) Multiclone

(8) "Wetted Screen"

Coal dust concentrations fed to the test scrubber were of the order of 0.01 gr/SCF. This relatively low level together with pre-removal of the oversize by use of an upstream cyclone in series with the scrubber ensured the absence of agglomerates in the scrubber feed dust. The particle size of the test coal dust was about 1.5-2.5 microns, with standard deviations of the same order of magnitude.

2(a). Venturi Scrubbers: Venturi, "Ventri-Rod" and "Ventri-Sphere"

The Calvert and Legatski data afford a rigorous test of the proposed $(C_d)(W/G)$ correlation parameter, and the calculated X_c values for the Venturi and "Ventri-Rod" Scrubber test data are presented in Tables 4-3 and 4-4, and Figure 4-8. Comparison of Table 4-3 and 4-4 with Figure 4-8 will show that the points plotted are the individual samples composing a single run. In view of the fact that the Venturi data were obtained at only one (W/G) level, and the "Ventri-Rod" data at only two, the only factor providing an adequate X_c range in Figure 4-8 was the random variation in inlet dust loading. As Figure 4-8 indicates, the gross penetration values associated with the random variations of the independent variable are quite clearly dependent on these variations. It is rather

TABLE 4-3

GROSS PENETRATION FOR A VENTURI SCRUBBER FOR AN INLET DUST OF MEAN DIAMETER 1.35 MICRONS AND STANDARD DEVIATION 1.7

DATA OF CALVERT AND LEGATSKI (1970)

Run	Configuration	Water Rate gal./MCF	Sample No.	Concentration (mg./SCM)	Concentration (gr./SCF)	$(C_i)(W/G)$(1)	Penetration %
79	No Rods	5.0	And.(2)	40.9	0.0179	0.089	42
			435	52.8	0.0231	0.115	39
			438	48.8	0.0213	0.106	39
80	No Rods	5.0	441	48.4	0.0212	0.106	36
			And.	38.1	0.0166	0.083	43
			444	48.8	0.0170	0.085	37
			446	52.5	0.0229	0.114	35
			Average	47.2	0.0206	0.103	38
81	No Rods	10.0	And.	46.3	0.0202	0.202	21
			449	50.2	0.0219	0.219	21
			452	51.9	0.0227	0.227	19
			454	52.7	0.0230	0.230	17
			Average	50.3	0.0220		19

TABLE 4-3 Cont'd.

Run	Configuration	Water Rate gal./MCF	Sample No.	Concentration (mg./SCM)	Concentration (gr./SCF)	(C$_d$)(W/G)	Penetration %
82	Rods	5.0	459	47.4	0.0207	0.104	44
			And.	37.5	0.0164	0.082	49
			462	44.9	0.0196	0.098	46
			464	47.3	0.0207	0.104	41
83	Rods	5.0	And.	33.8	0.0148	0.074	48
			467	42.4	0.0185	0.092	42
			470	43.1	0.0188	0.094	40
			472	43.0	0.0188	0.094	40
			Average	42.4	0.0185	0.092	43

(1) (gr./SCF)(gal./MCF)
(2) Andersen Sampler

TABLE 4-4

GROSS PENETRATION FOR A "VENTRI-ROD" SCRUBBER FOR A COAL DUST OF MEAN DIAMETER 1.42 MICRONS AND STANDARD DEVIATION 1.64

DATA OF CALVERT AND LEGATSKI (1970)

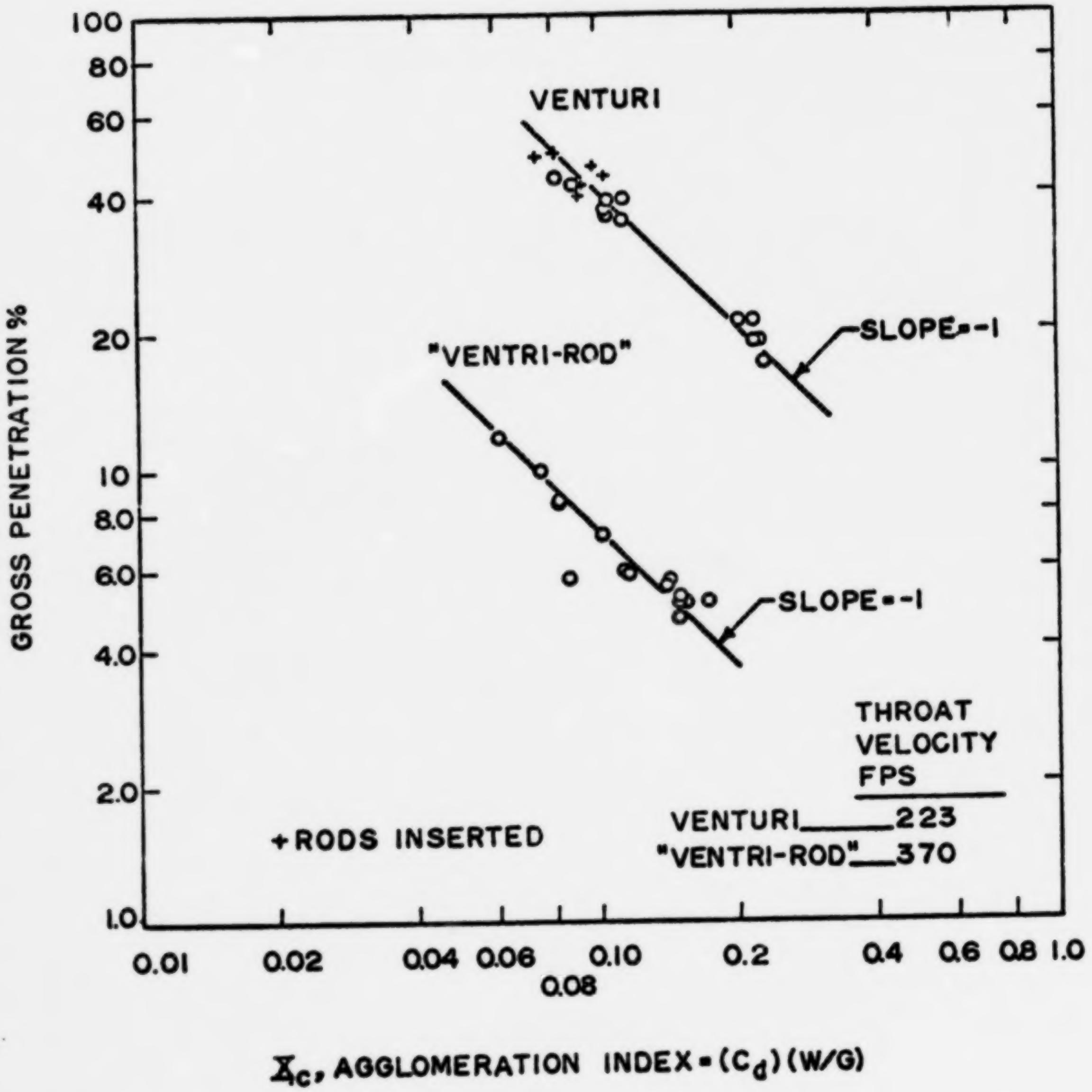
Run	Water Rate gal./MCF	Sample No.	Concentration		$(C_d)(W/G)^{(1)}$	Penetration %
			(mg./SCM)	(gr./SCF)		
86	6	489	31.2	0.0136	0.0817	8.3
		And.$^{(2)}$	23.3	0.0102	0.0612	11.6
		492	28.3	0.0124	0.0744	9.9
		494	31.0	0.0136	0.0816	8.4
		Average	28.5	0.0125		9.4
87	10	And.	19.5	0.00852	0.085	6.4
		497	26.4	0.0115	0.115	5.8
		500	31.9	0.0139	0.139	5.5
88	10	503	34.0	0.0149	0.149	5.2
		And.	25.6	0.0112	0.112	5.9
		506	34.3	0.0150	0.150	5.2
89	10	And.	23.4	0.0102	0.102	7.1
		509	32.2	0.0141	0.141	5.6
		512	35.0	0.0153	0.153	5.0
		514	34.0	0.0149	0.149	4.7
		Average	29.6	0.0129		5.5

(1) (gr./SCF)(gal./MCF)
(2) Andersen sampler

FIGURE 4-8

VENTURI AND "VENTRI-ROD" SCRUBBERS GROSS PENETRATION AS FUNCTION OF AGGLOMERATION INDEX, $(C_d)(W/G)$

DATA OF CALVERT & LEGATSKI (1970)



remarkable that the agglomeration index approach is sensitive enough to show correlation for what would ordinarily be presumed to be random experimental sample error, as was assumed by Calvert and Legatski.

Despite the absence of deliberate changes in the primary variables, and the necessary use of supposedly incidental variations, both sets of data correlate quite well with the -1 slope found for the Ingels' asphalt plant scrubber data, substantiating the earlier tentative conclusion of a simple inverse relationship between gross penetration and X_c. The relationships shown in Figure 4-8 are of the form:

$$F = \frac{K}{(C_d)(W/G)} \qquad (4\text{-}2)$$

where F = penetration, weight percent

K = proportionality constant

At constant gas velocity or pressure drop, Equation (4-2) can obviously be used to compare scrubber performance. The "K" value may be looked upon as a relative performance index, with a smaller value denoting superior performance. For the data of Figure 4-8, using the conventional units for C_d and (W/G):

Venturi: K = 4.13

"Ventri-Rod": K = 0.724

This K comparison, indicating lower penetration values for the "Ventri-Rod" unit as compared to the Venturi, is illustrative and not absolute because of a substantial velocity difference in the two sets of runs. Part of the performance difference indicated by the relative K values may be attributed to the fact that the "Ventri-Rod" scrubber was operated at a throat velocity of 370 fps, which is 70% greater than the 223 fps velocity used in the Venturi. However, even after correcting for the velocity differential on the basis of the velocity ratio squared, the "Ventri-Rod" unit still shows substantially better performance than the Venturi using the agglomeration index approach. It is interesting that no comparable conclusion was drawn by Calvert and Legatski, using the conventional impaction theory approach.

In contrast to the direct tests on the commercial "Ventri-Rod" unit some additional limited data were run on a home-made Venturi, with and without throat rods. In the test series on the Venturi scrubber, Table 4-3, two runs (eight samples) were made with rods inserted below the throat, and Calvert and Legatski concluded that the presence of these rods had a negative effect on the scrubbing efficiency. Figure 4-8 shows that, as a group, the penetrations for the rods-inserted runs were slightly greater than for the Venturi runs made without the rods. However, it is quite clear that the reason for this apparent shift is the lower values of the agglomeration index(run conditions) and that the rod data correlate with the rest of the data, and their insertion is without effect on penetration. The agglomeration index would thus seem to have a good deal of potential as an analytical tool at the experimental level in differentiating between random or real effects. Further, it is apparent that a valid performance evaluation requires comparison under similar X_c conditions.

Another modification of the Venturi that was tested by Calvert and Legatski was a "Ventri-Sphere" scrubber, which consists of a Venturi section with a long diffuser section, a 180° gas reversal, and a 1-foot deep flooded bed of plastic spheres in the annular space surrounding the Venturi. Data for these tests are provided in Table 4-5 and are plotted in Figure 4-9. The tests were made at two different Venturi throat velocities, and despite the absolute values of penetration, the data appear to confirm the expectation of a lower penetration line for equal values of X_c at the higher throat velocity. However, point scatter is severe at these lower penetration levels (higher X_c) and it is apparent that the combination of inlet dust concentrations of the order of 0.02 gr/CF and removals of 99% have reached the limits of experimental measurement capability. Despite this, both lines in Figure 4-9 were drawn with a -1 slope and appear to reasonably represent the data. The penetration data for the "Ventri-Sphere" fall below the line in Figure 4-8 for the "Ventri-Rod" scrubber, indicating that, at projected similar throat velocities, the flooded bed does actually contribute some additional dust removal capability.

2(b). Impingement Scrubber

The impingement scrubber tested on the coal dust consisted of two stages of standard-design impingement plates, with a tangential gas inlet (cyclone effect) below the stages.

TABLE 4-5

GROSS PENETRATION FOR A "VENTRI-SPHERE" SCRUBBER FOR AN INLET DUST OF MEAN DIAMETER 1.44 MICRONS AND STANDARD DEVIATION 1.7

DATA OF CALVERT AND LEGATSKI (1970)

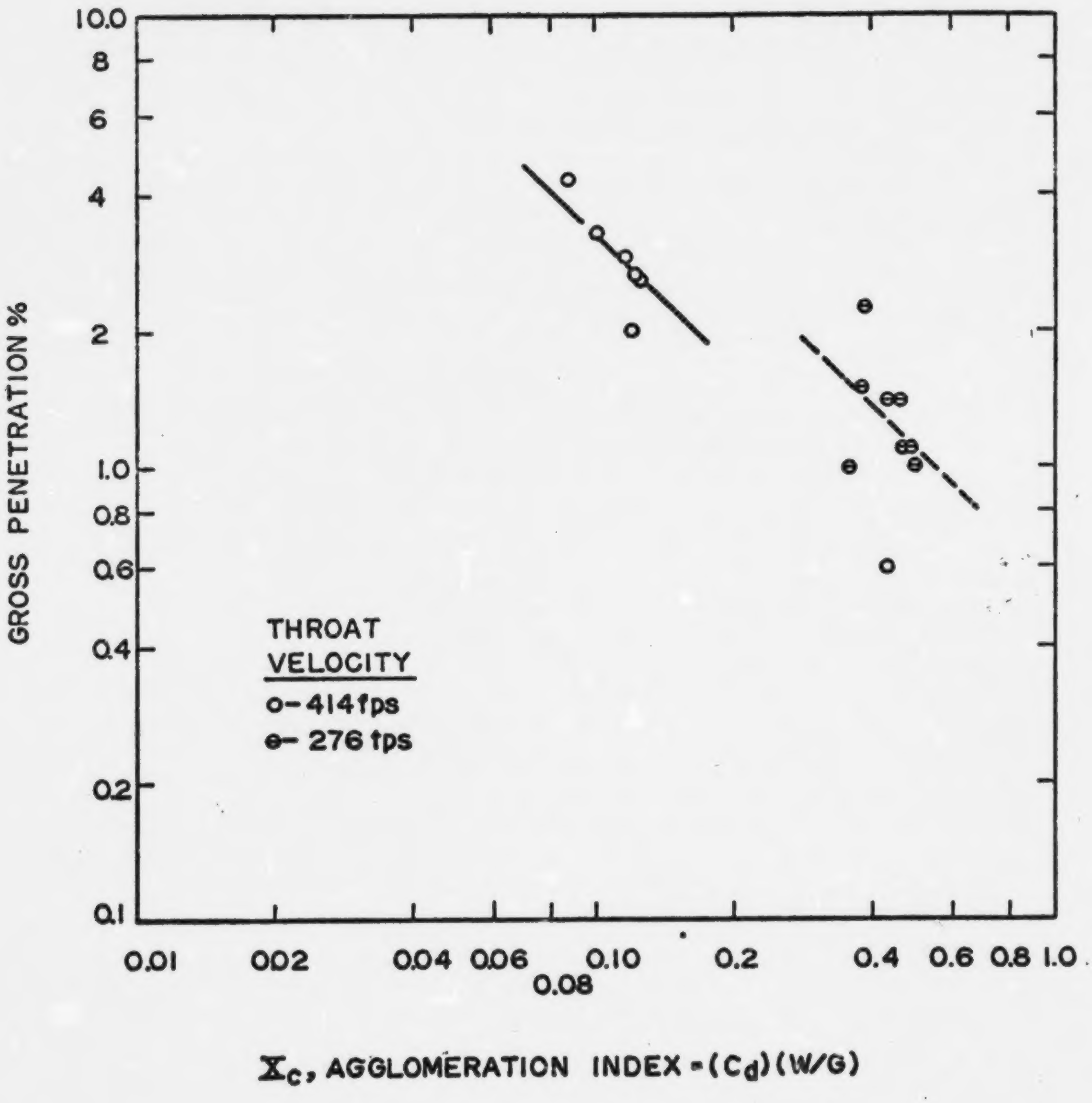
Run	Water Rate gal./MCF	Air Rate CFM	Sample No.	Concentration (mg./SCM)	Concentration (gr./SCF)	$(C_d)(W/G)^{(1)}$	Penetration %
95	16.7	1500	And.$^{(2)}$	48.2	0.0210	0.350	1.0
			547	58.7	0.0256	0.427	0.6
			550	63.0	0.0275	0.459	1.4
96	16.7	1500	553	59.0	0.0258	0.431	1.4
			And.	52.0	0.0227	0.379	1.5
			556	64.3	0.0281	0.469	1.1
97	16.7	1500	And.	52.6	0.0230	0.384	2.2
			559	65.9	0.0288	0.481	1.1
			562	67.6	0.0295	0.493	1.0
			Average	59.0	0.0258	0.431	1.2
98	5.0	2000	565	53.1	0.0232	0.116	2.9
			And.	46.5	0.0203	0.101	3.3
			568	56.1	0.0245	0.122	2.6

TABLE 4-5 Cont'd.

Run	Water Rate gal./MCF	Air Rate CFM	Sample No.	Concentration (mg./SCM)	Concentration (gr./SCF)	$(C_d)(W/G)$	Penetration %
99	5.0	2000	And.	41.0	0.0179	0.089	4.3
			571	55.2	0.0241	0.120	2.0
			574	56.7	0.0248	0.124	2.6
			Average	51.4	0.0224	0.112	2.9

(1) (gr./SCF)(gal./MCF)
(2) Andersen Sampler

FIGURE 4-9
"VENTRI-SPHERE" SCRUBBER
GROSS PENETRATION AS FUNCTION
OF
AGGLOMERATION INDEX, (C_d) (W/G)
DATA OF CALVERT & LEGATSKI (1970)



The scrubber was 2.5 ft in diameter, and the trays had 22% open area, yielding a free flow area of 0.68 ft^2. The unit was operated with a countercurrent liquid flow rate (sprayed in) of 20 GPM and in one set of runs this was augmented with a 20 GPM cocurrent flushing spray directed at the bottom plate. The data for these runs are presented in Table 4-6 and Figure 4-10.

On an impingement plate, the atomization of the water occurs at the tray orifices, and the degree of this atomization is nominally a function of the liquid depth, and hence the counter-current liquid rate. The bottom spray serves to keep the underside of the bottom plate washed free of accumulated solids, and since it contacts the gas at low gas energy levels, the contribution of this flushing liquid rate would not normally be counted toward (W/G). This procedure was originally followed in plotting the data of Table 4-6. However, it was found that when all of the data of Table 4-6 were plotted in this manner, without differentiation for the use of the auxiliary spray, it was virtually impossible to discern any pattern in the point grouping. Therefore, the data were separated into two groups, depending on whether or not the bottom spray was used, and were re-plotted as shown in Figure 4-10.

Figure 4-10 shows that the set of penetration data obtained without the bottom spray conforms to the reciprocal X_c relationship already established, and further, that the comparative penetrations for the two-spray data are all lower than the best penetration-X_c line for the single-spray data. Thus, it may be concluded that the bottom spray is providing a small, but definite, incremental contribution to the efficiency of the unit. This is in direct contradiction to the conclusions of Calvert and Legatski, who, on the basis of the original Table 4-6 data, decided that "the gross penetration... appears to be essentially unaffected by the plate spray for this particular dust". Again, this illustrates the utility and sensitivity of the agglomeration index approach, and its general applicability regardless of equipment type. The relatively poor performance of the impingement scrubber as compared to the various Venturi units discussed above may be attributed to the fairly low maximum (orifice) velocity of 61.2 fps.

2(c). "Air Tumbler"

This device is a horizontal wet cyclone containing a water well, and the cyclonic action of the air causes

TABLE 4-6

GROSS PENETRATION FOR AN IMPINGEMENT SCRUBBER FOR AN INLET DUST OF MEAN DIAMETER 1.44 MICRONS AND STANDARD DEVIATION 1.7

DATA OF CALVERT AND LEGATSKI (1970)

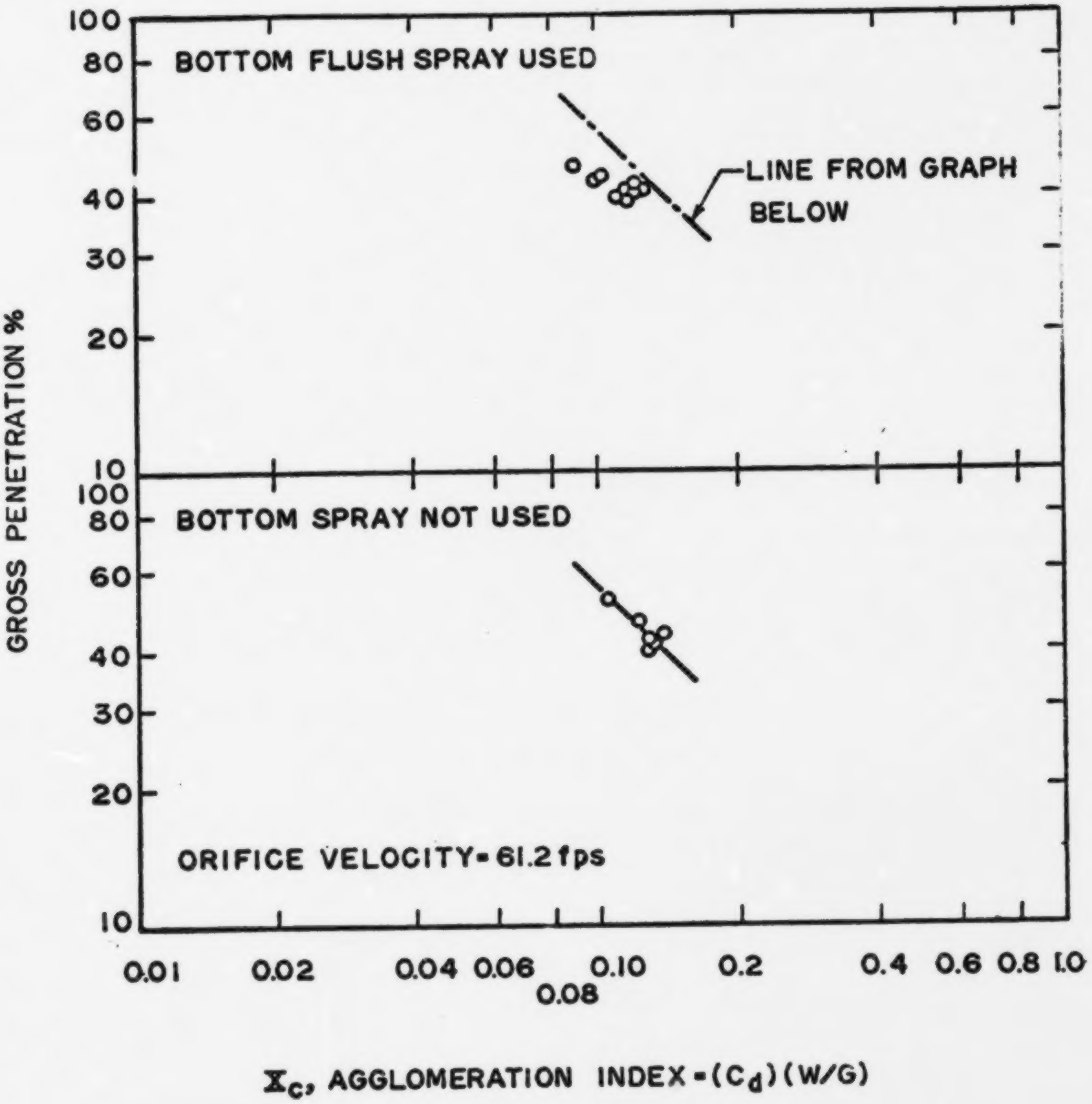
Run	Spray Water Rate gal./MCF		Sample No.	Concentration		$(C_d)(W/G)$(1)	Penetration %
	Top	Bottom		(mg./SCM)	(gr./SCF)		
90	8	8	517	35.0	0.0153	0.122	42.3
			And.(2)	29.2	0.0128	0.1024	43.8
			520	36.2	0.0158	0.126	40.3
91	8	8	And.	25.4	0.0111	0.0888	46.1
			523	31.6	0.0138	0.1104	39.6
			526	33.5	0.0146	0.117	38.2
92	8	8	529	33.5	0.0146	0.117	40.9
			And.	28.6	0.0125	0.100	42.7
			532	34.9	0.01525	0.122	40.1
			Average	32.0			41.4
93	8	0	And.	31.4	0.0137	0.110	52.2
			535	36.4	0.0159	0.127	40.1
			538	39.0	0.0170	0.136	43.8

TABLE 4-6 Cont'd.

Run	Spray Water Rate gal./MCF		Sample No.	Concentration		$(C_d)(W/G)$	Penetration %
	Top	Bottom		(mg./SCM)	(gr./SCF)		
94	8	0	531	36.4	0.0159	0.127	42.3
			And.	34.2	0.0150	0.120	46.2
			544	37.1	0.0162	0.130	41.5
			Average	35.8			44.1

(1) (gr./SCF)(gal./MCF)
(2) Andersen Sampler

FIGURE 4-10
2-STAGE IMPINGEMENT SCRUBBER
GROSS PENETRATION AS FUNCTION
OF
AGGLOMERATION INDEX, (C_d) (W/G)
DATA OF CALVERT & LEGATSKI (1970)



pickup and dispersion of the liquid from the well. In this mode of operation, the liquid feed rate to the equipment is not directly related to the actual dispersed-water/gas ratio in the contact zone. The data for the single run made by Calvert and Legatski for this unmodified unit are given in Table 4-7, and the gross penetration of the 1.35-micron dust was a high 58%. The unit was modified by the insertion of a "flushing device" at the gas entrance which raised the point velocity at this section to 100 fps; this was termed "Configuration 2". A second modification, "Configuration 3", consisted of the addition of a low-energy Venturi section (throat velocity = 200 fps) between the flushing device and the "Air Tumbler" proper, and data for these runs are also listed in Table 4-7.

No description of the flushing device or the allocation of water to the various components in series was provided, so that it was not possible to calculate any meaningful (W/G) ratios for these runs. Instead, the gross penetration data were plotted against inlet dust loadings in Figure 4-11, and by separation of the runs by configuration and gross water rates, a degree of data order is achieved. For Configuration 2, at 2.5 GPM, the data agree quite well with the expectation of a reciprocal penetration-C_d relationship. Raising the gross flow rate to 7.5 GPM (with unspecified distribution) at this same configuration gave a group of data points showing somewhat higher penetrations, rather than the lower values to be expected. Without a description of the "flushing device", it is not possible to further evaluate these negative results. However, for the Venturi section-addition of Configuration 3, lower penetrations are obtained at the higher gross water rates, as would be expected from previous agglomeration index behavior patterns. In addition to the absence of required information on the physical aspects of the equipment, no cross-sectional area data was provided for the main cyclone body, and linear velocities could not be estimated from the stated volumetric flow rate of 2200 CFM.

2(d). Packed Bed Scrubber and Multiclone

As part of the scrubber study conducted by Calvert and Legatski, tests were made on a Multiclone unit, operated dry, and a 3-foot deep bed packed with 1-1/2" polypropylene pall rings, operated both dry and wet. The data for these runs are tabulated in Tables 4-8, 4-9 and 4-10, and are plotted in Figure 4-12.

TABLE 4-7

GROSS PENETRATION FOR AN "AIR TUMBLER" FOR AN INLET DUST OF MEAN DIAMETER 1.35 MICRONS AND STANDARD DEVIATION 1.7

DATA OF CALVERT AND LEGATSKI (1970)

Run	Configuration	Nominal Water Rate gal./MCF	Sample No.	Concentration		$(C_d)(W/G)^*$	Penetration %
				(mg./SCM)	(gr./SCF)		
77	1	7.5	426	38.7	0.0169	0.1268	58
71	2	2.5	374	56.4	0.0246	0.0615	33
			And.**	56.0	0.0244	0.0610	28
			377	44.6	0.0195	0.0488	69
			379	65.4	0.0285	0.0713	28
72	2	2.5	And.	40.0	0.0175	0.0438	41
			382	54.9	0.0240	0.0600	33
			385	57.0	0.0249	0.0623	31
73	2	2.5	388	51.4	0.0224	0.0560	36
			And.	38.1	0.0166	0.0415	44
			391	51.4	0.0224	0.0560	36
			393	50.2	0.0219	0.0548	36
			Average	51.4	0.0224	0.0560	37

TABLE 4-7 Cont'd.

Run	Configuration	Nominal Water Rate gal./MCF	Sample No.	Concentration		$(C_d)(W/G)$	Penetration %
				(mg./SCM)	(gr./SCF)		
74	3	2.5	And.	40.4	0.0176	0.0440	51
			396	54.5	0.0238	0.0595	42
			399	55.1	0.0241	0.0603	41
			401	56.9	0.0248	0.0620	41
			Average	51.7	0.0226		43
75	3	10.3	404	66.2	0.0289	0.298	31
			407	68.7	0.0300	0.309	30
			409	69.1	0.0303	0.312	30
			And.	60.4	0.0264	0.272	30
76	3	10.3	413	61.2	0.0267	0.275	33
			And.	48.4	0.0211	0.217	37
			416	65.8	0.0287	0.295	32
			418	64.2	0.0280	0.288	32
			Average	63.0	0.0275	0.283	32

TABLE 4-7 Cont'd.

Run	Configuration	Nominal Water Rate gal./MCF	Sample No.	Concentration (mg./SCM)	Concentration (gr./SCF)	$(C_d)(W/G)$	Penetration %
77	2	7.5	And.	43.2	0.0189	0.142	31
			421	49.5	0.0216	0.162	38
			424	48.3	0.0211	0.158	39
78	2	7.5	429	68.7	0.0300	0.225	32
			And.	57.5	0.0251	0.188	33
			432	77.8	0.0340	0.255	30
			Average	57.5	0.0251	0.188	34

* (gr./SCF)(gal./MCF)
** Andersen Sampler

1 Air Tumbler Alone
2 Air Tumbler with "Flushing Device"
3 Air Tumbler with Venturi and "Flushing Device"

FIGURE 4-11

"AIR TUMBLER"

GROSS PENETRATION AS FUNCTION OF INLET DUST LOADING

DATA OF CALVERT & LEGATSKI (1970)

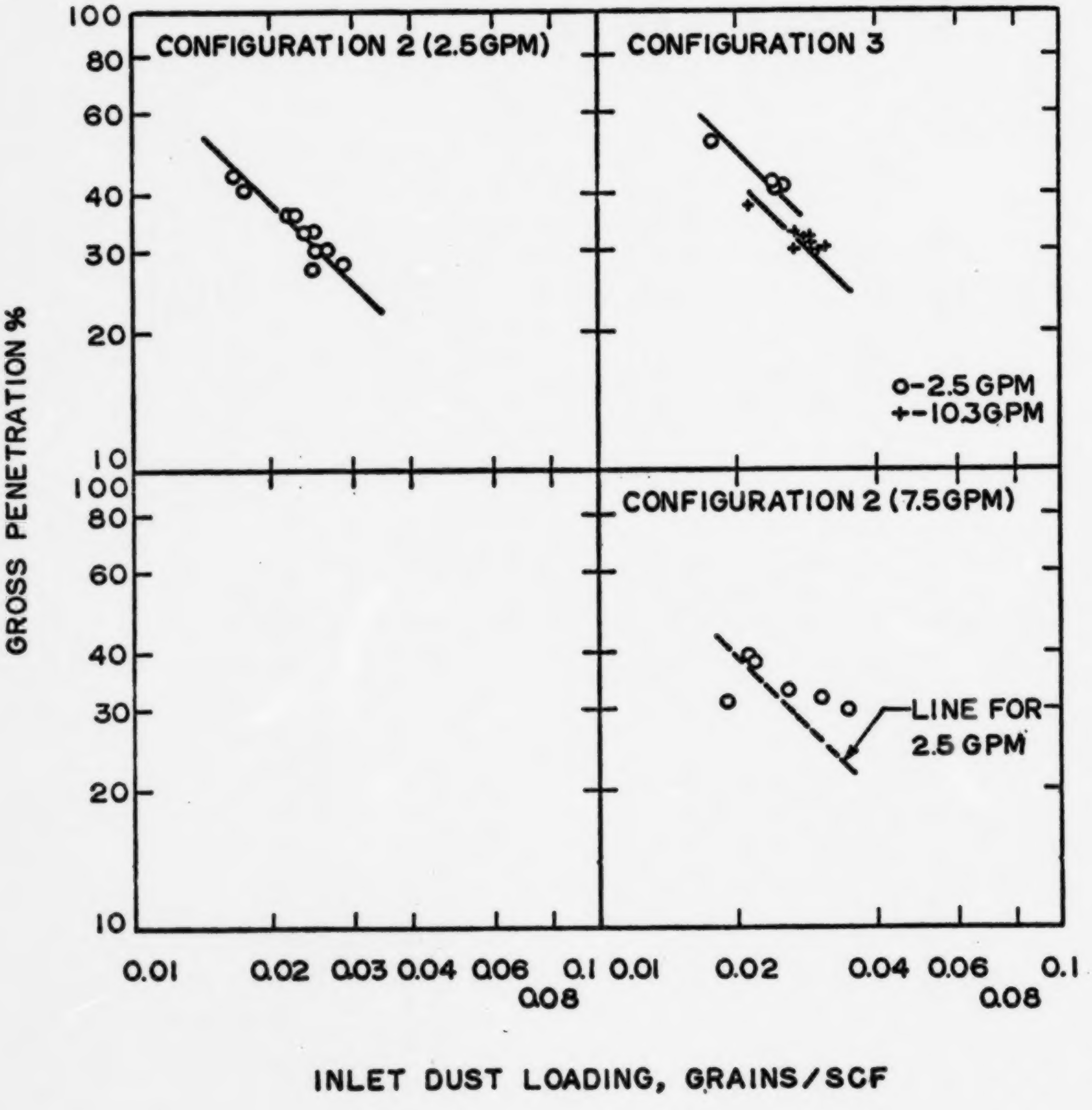


TABLE 4-8

GROSS PENETRATION FOR A DRY PACKED BED SCRUBBER FOR AN INLET DUST OF MEAN DIAMETER 1.82 MICRONS AND STANDARD DEVIATION 1.68

DATA OF CALVERT AND LEGATSKI (1970)

Run	Sample No.	Concentration (mg./SCM)	Concentration (gr./SCF)	Penetration %
57	And.*	11.7	0.00511	40
	269	10.7	0.00467	30
	271	12.0	0.00524	38
58	276	10.2	0.00446	46
	278	13.8	0.00603	35
	And.	8.8	0.00385	42
	Average	11.2	0.00489	39

* Andersen Sampler

TABLE 4-9

GROSS PENETRATION FOR A WET PACKED BED SCRUBBER FOR AN INLET DUST OF MEAN DIAMETER 1.44 MICRONS AND STANDARD DEVIATION 1.74
W/G = 2.0 gal./MCF

DATA OF CALVERT AND LEGATSKI (1970)

Run	Sample No.	Concentration (mg./SCM)	Concentration (gr./SCF)	$(C_d)(W/G)^{(1)}$	Penetration %
63	314	13.6	0.00594	0.0119	29
	316	13.9	0.00612	0.0122	43
	And.(2)	12.9	0.00564	0.0113	26
64	And.	15.4	0.00673	0.0135	36
	326	15.1	0.00660	0.0132	26
	328	15.7	0.00686	0.0137	36
65	332	13.8	0.00603	0.0121	27
	And.	13.2	0.00577	0.0115	27
	334	15.3	0.00669	0.0134	31
66	340	14.4	0.00629	0.0126	33
	And.	10.9	0.00476	0.00952	47
	342	15.6	0.00682	0.0136	38
	Average	14.15			33

(1) (gr./SCF)(gal./MCF)
(2) Andersen Sampler

TABLE 4-10

GROSS PENETRATION FOR A MULTICLONE FOR AN INLET DUST OF MEAN DIAMETER 1.5 MICRONS AND STANDARD DEVIATION 1.7

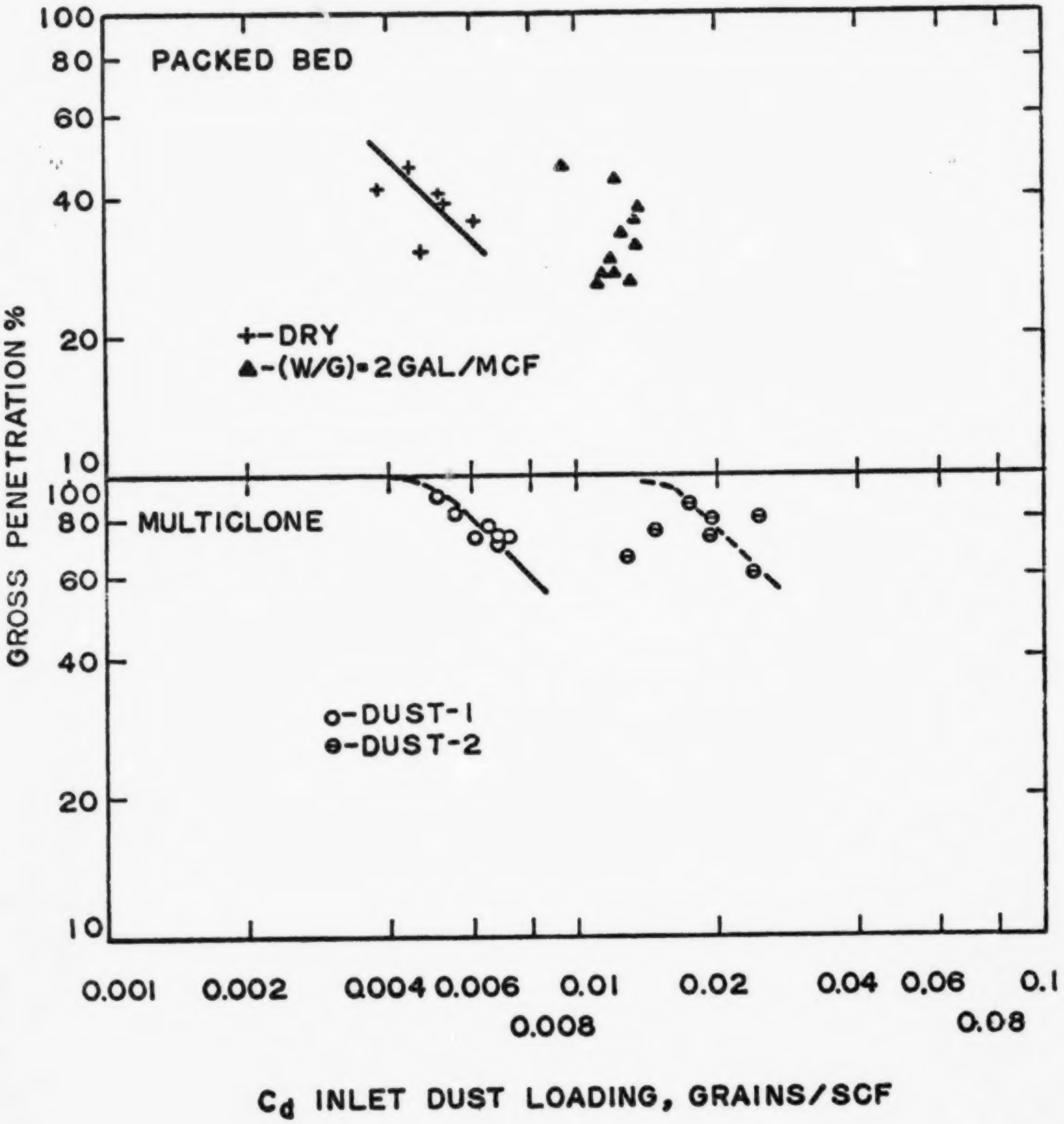
DATA OF CALVERT AND LEGATSKI (1970)

Run	Sample No.	Concentration (mg./SCM)	Concentration (gr./SCF)	Penetration %
67	And.*	12.6	0.0550	82.5
	348	15.3	0.0668	73.9
	346	15.5	0.0677	70.3
	351	14.1	0.0616	72.3
68	355	14.9	0.0650	77.2
	And.	11.6	0.0507	89.7
	357	16.4	0.0716	73.2
69**	393	44.3	0.1934	73.8
	And.	29.4	0.1284	66.7
	360	33.7	0.1472	75.4
	365	43.7	0.1909	80.1
70	368	54.6	0.238	60.6
	And.	39.7	0.1733	86.1
	371	56.1	0.245	80.4

* Andersen Sampler

** A new dust was used starting with Run #69

FIGURE 4-12
DRY & WET PACKED BED SCRUBBER & MULTICLONE
GROSS PENETRATION AS FUNCTION OF AGGLOMERATION INDEX OR DUST LOADING
DATA OF CALVERT & LEGATSKI (1970)



Both types of scrubbers tested in this series are inertial impaction units which do not depend on dust-particle/water-droplet collisions for agglomeration to critical removal size. Therefore, the collision function, or agglomeration index, used for correlation of the gross penetration behavior for drop/particle contacting should not be applicable to these units. However, in the absence of dispersed water droplets, the self-agglomeration of dust in the turbulent or inertial field should be a function solely of the inlet dust concentration, C_d, as shown by the data previously plotted. The results of Figure 4-12 are in accord with this expectation. The dry packed bed data and the first set of multiclone runs appear to correlate well with the $(C_d)^{-1}$ relation. However, the second set of dry Multiclone runs at the higher dust loadings shows too great a degree of point scatter to permit more than an indication of the possible position of the correlating line. Reference to Table 4-10 shows that the investigators made specific note of the fact that a "new dust" was used for the second set of Multiclone runs, but gave no reason for the accompanying shift to higher weight dust loadings. The relative position of this second set of data on the C_d plot is evidence that the most probable cause was a marked change in particle size distribution, but no analytical data on this point were provided.

The packed bed data of Figure 4-12 show a fair correlation on a C_d basis for the dry runs, but a completely random pattern for the wet runs at a constant (W/G) = 2.5 gal/MCF. Because the dry bed causes the gas to follow a tortuous, curved path, inertial and self-agglomeration behavior similar to the Multiclone unit would be expected for the dry dust, and this is substantially the observed behavior. The displacement of the wet-run packed-bed points to the right in Figure 4-12 results from the use of the $(C_d)(W/G)$ index for these data rather than C_d alone; the latter is the most probably correct variable in this test situation. The wet-run data scatter may result either from the narrow range of inlet dust loadings employed, the extremely low values of dust loading, or from gas backmixing and recirculation caused by the opposing water flow in the countercurrent contact packed bed. Within the limitations of the data, there appears to be no particular advantage, from a gross penetration basis, of wet countercurrent packed bed operation, as compared to dry operation at these dust loading levels.

If the scrubber performance is dependent on inlet dust loadings, as the data have thus far indicated, then it would appear mandatory that comparative equipment tests be carried out using similar dust concentrations. An inspection of the tabulated Calvert and Legatski data in this report will show that the packed bed and Multiclone runs, as well as those for the "wetted screen" discussed below, were made at inlet coal dust loadings roughly 25% of those used for the Venturi and other equipment types. The relatively high gross percentage penetration levels of Figure 4-12 associated with these low loadings are indicative of the seemingly anomalous data resulting from allowing order-of-magnitude variations in the inlet dust concentration test conditions. Failure to hold this primary variable within reasonably narrow test limits would tend to invalidate any conclusions drawn from data uncorrected for this variation. Correction to a comparable C_d (or X_c) basis should be made by the method of Lapple and Kamack (1955) of extrapolating to an arbitrary fixed dust loading value, or by the direct graphical method employed in this report.

2(e). "Wetted Screen" Scrubber

This unit consisted of a pleated, accordion-like sprayed-screen assembly, followed by a horizontal cyclone separator. Data for the tests on this unit are presented in Table 4-11 and in Figure 4-13, and inspection again indicates that failure to allow for the dust loading dependency seriously compromised the conclusions drawn from the test results. The data of Figure 4-13 scatter badly, but in view of the very low X_c test levels, this is not unexpected. The low agglomeration index values arise not only from the low dust loading concentrations of 0.005 gr/SCF, but also from the small (W/G) ratio of 0.75 gal/MCF. With due consideration for these latter values, the penetration values obtained are remarkably low, indicating excellent unit performance, which is directly contrary to the conclusions of the investigators. While it is by no means certain from the data of Figure 4-13 that the penetration/X_c reciprocal relationship applies, if a 45° line drawn through the data is extended to the higher X_c ranges used for testing the Venturi-type scrubbers, lower comparative gross penetrations are indicated for the wetted screen scrubber. However, such unit comparison on an X_c basis is not fully warranted on the basis of present data, in view of the wide ranges of linear velocity variation and the absence of a pressure drop or energy consumption data base for these data. In addition to the need for pressure drop information, the questions of the relation of the penetration/agglomeration index dependency to mean particle size and particle size distribution remain to be answered.

TABLE 4-11

GROSS PENETRATION FOR THE "WETTED SCREEN" SCRUBBER FOR AN INLET DUST OF MEAN DIAMETER 1.5 MICRONS AND STANDARD DEVIATION 1.8

DATA OF CALVERT AND LEGATSKI (1970)

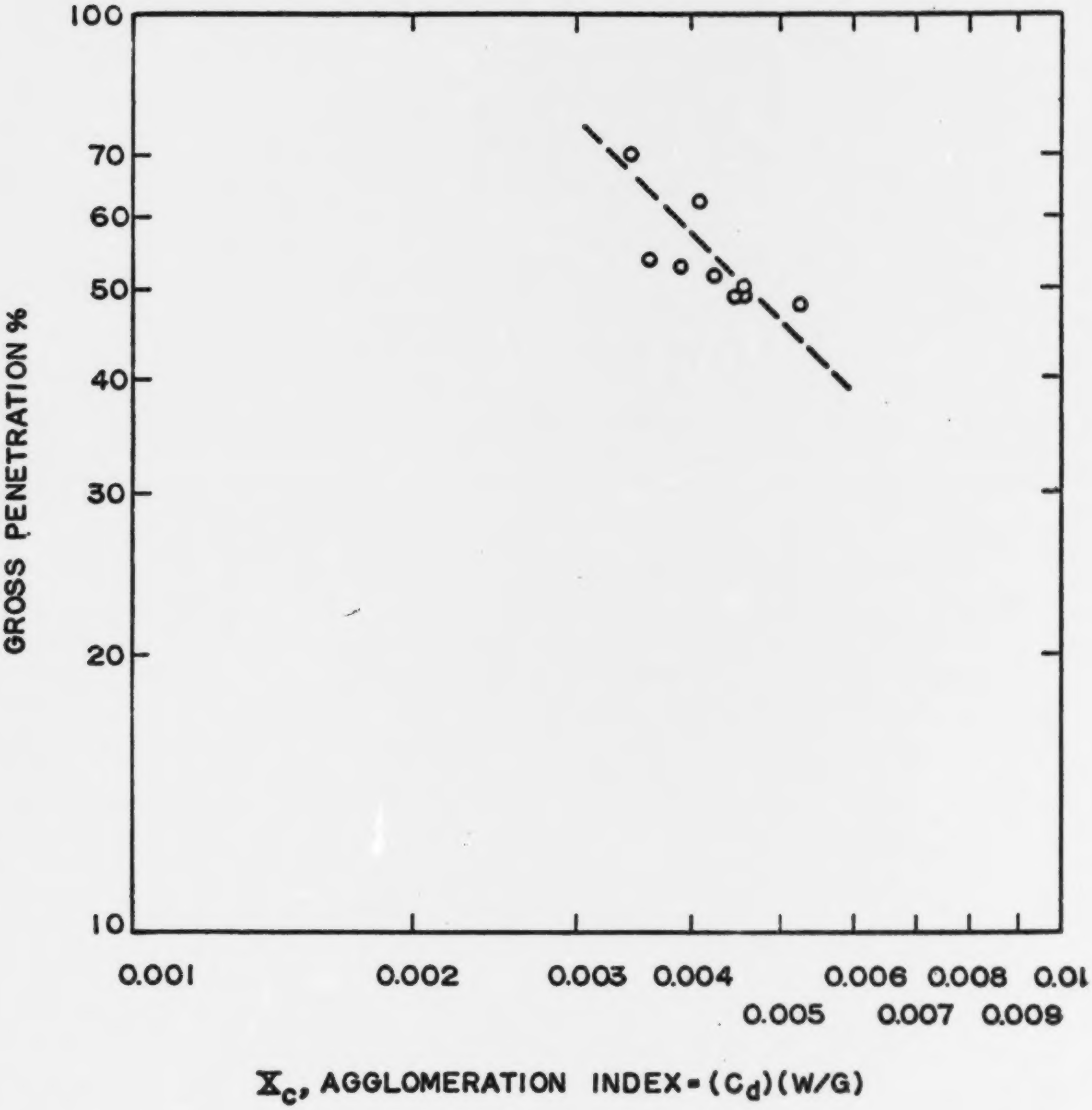
Run	Sample No.	Concentration		$(C_d)(W/G)^{(1)}$	Gross Penetration %
		(mg./SCM)	(gr./SCF)		
60	And.(2)	10.5	0.00459	0.00344	70
	297	11.9	0.00520	0.00390	53
	293	13.4	0.00586	0.00439	49
61	And.	16.1	0.00704	0.00528	48
	304	13.9	0.00608	0.00456	49
	302	13.9	0.00608	0.00456	50
62	And.	11.0	0.00481	0.00360	54
	308	12.5	0.00546	0.00409	62
	310	12.9	0.00564	0.00423	51

Air Rate = 2400 CFM
Water Rate = 1.8 GPM

(1) (gr./SCF)(gal./MCF)
(2) Andersen Sampler

FIGURE 4-13

WETTED SCREEN SCRUBBER
GROSS PENETRATION AS FUNCTION
OF
AGGLOMERATION INDEX $(C_d)(W/G)$
DATA OF CALVERT & LEGATSKI (1970)



E. PARTICLE SIZE EFFECTS

Meaningful literature data on wet scrubber performance as a function of particle size and/or size distribution are very limited. While Lapple and Kamack (1955) tested a group of aerosols of varying mean diameters and size distributions, as did Kristal, Dennis and Silverman (1955), comparison of scrubber efficiencies for different dusts is complicated by the probable secondary effects of chemical and physical variations. This problem was encountered by Lapple and Kamack, who observed that their ilmenite test dust showed anomalous behavior when compared to talc dusts, and found it necessary to separate scrubber performance data according to the test dust used. What is therefore required are data on the effect of particle size and distribution variation on scrubber performance for a single dust. The investigation of Calvert and Legatski on coal dust comes closest to meeting this requirement, but unfortunately was necessarily limited to a very narrow range of respirable dust size. Nevertheless, as is strikingly indicated in Figure 4-12, an apparently small change in dust size characteristics produced a major shift in the position of the penetration/X_C line for the Multiclone. Again, this is a qualitative interpretation, inasmuch as no quantitative data were provided. Within the restricted limits of the available data, only a limited projection of the probable size effects on penetration performance of wet scrubbers is presently possible, and this would appear to be an attractive area for productive research.

1. Particle Size Distribution

An appreciable part of the problem of relating particulate scrubber performance to particle size lies in the proper determination and use of an applicable mean or representative particle size for a distribution of sizes in a given dust. There are three mean particle diameter terms in common use, and these are defined as:

(1) Number or count median diameter is the diameter for which half of the total number of particles have a larger (or smaller) diameter.

(2) Mass median diameter is the diameter for which half the total volume of the particles is contained in particles larger (smaller) than this diameter.

(3) Specific surface-average or Sauter diameter is usually applied to liquid drop swarms and is the diameter of a single drop with the same ratio of surface to volume as the total sum of drops.

The relationships between mean particle sizes and size distributions is covered in standard texts such as Drinker and Hatch (1954) and will not be detailed here. However, because scrubber efficiency is generally expressed as weight per cent, the mass median diameter and mass distribution are the primary terms of interest. For dusts which follow a logarithmic normal size distribution, it is possible to convert the count median diameter, D_c, to the mass median diameter, D_g, by the relation:

$$\ln(D_g) = \ln(D_c) + 3[\ln(\sigma_g)]^2 \qquad (4\text{-}3)$$

where

σ_g = geometric mean deviation

The obvious sensitivity of D_g to the geometric mean deviation for D_c data in Equation (4-3) imposes stringent requirements on the analytical distribution data which are difficult to obtain experimentally.

Davis and Truitt (1971) have presented a simple and significant statement of a normalized mass concentration function in terms of particle diameter which has been found to fit the experimental data for many aerosol emissions. This expression is:

$$(1/M)dM/dD = [1/\ln(Dmax/Dmin)] \qquad (4\text{-}4)$$

where

M = mass concentration

D = particle diameter

max, min = maximum and minimum, respectively

It is believed that this equation has potential utility in the interpretation of wet scrubbing performance data, and this will be explored below in connection with the data of Kristal, Dennis and Silverman (1957).

2. Data of Kristal, Dennis and Silverman (1957)

These investigators tested the scrubbing performance of a Solivore scrubber with a number of aerosols: covering a wide range of mass median particle sizes and inlet dust loadings. Penetration test data were obtained for several aerosols at varying water rate runs, and for a separate series of varying inlet dust loading runs; these data are presented in Tables 4-12A and 4-12B. Before analyzing these data in terms of the agglomeration index, it is necessary to review the methods of preparing and introducing the aerosols, inasmuch as these definitely affect the results.

The coarse H_2SO_4 mist was prepared by aspiration, followed by removal of the larger particles by impingement on a baffle in an elutriation chamber. Similarly, the $CuSO_4$ was produced by pneumatic nozzle atomization, followed by elutriation, and finally dehydration in a heated pipe. The fly ash, $CaCO_3$, and other solids were fed to the scrubber by means of the "Harvard generator" for loadings greater than 0.2 gr/CF, and the National Bureau of Standards gear-tooth/aspirator feeder was used for loadings in the range of 0.02 gr/CF. As noted earlier, the use of the latter two types of feeder involve the possibility of introducing pre-agglomerates or forming dry agglomerates in the venturi aspirator. The secondary elutriation and/or impingement treatment of the $CuSO_4$ and H_2SO_4 aerosols ensures the absence of agglomerations in the scrubber feed, and Figure 4-14 treats these two aerosols as comparable.

Figure 4-14 indicates that the limited penetration run data for the two aerosols fit the -45° agglomeration index line relationship previously found for both Ingels' data on asphalt mix plant dust, and Calvert and Legatski's coal dust penetrations. The agreement between the two sets of aerosols tests in Figure 4-14 is surprisingly good, and a single line could obviously be drawn for both sets of points rather than the individual lines actually shown.

While the $CuSO_4$ and H_2SO_4 aerosols were prepared by virtually identical methods, the fly ash and $CaCO_3$ materials in the Table 4-12A and 4-12B runs were fed to the scrubber by differing means. The data for the latter dusts are plotted in Figure 4-15, and the anomalous behavior, compared to Figure 4-14, is apparent. The line through the two $CaCO_3$ points has a slope of -0.4, indicating a possible pre-agglomeration effect with either one or both of the two different feeders used for the two points.

TABLE 4-12A

MULTI-VENTURI (SOLIVORE) SCRUBBER PENETRATION TEST DATA FOR THREE AEROSOLS AT VARYING WATER RATES

DATA OF KRISTAL, DENNIS AND SILVERMAN (1957)

Aerosol	W/G gal/1000 ft.^{3} of air	Inlet Dust Loading gr./ft.^{3}	$(C_d)(W/G)$	Weight Collection Efficiency %	Passage %
Fly Ash (14.3 micron)	20	0.2(1)	4.0	99.2	0.8
	30	0.2	6.0	99.4	0.6
	40	0.2	8.0	99.6	0.4
$CuSO_4$ (0.74 micron)	20	0.6/1000(2)	0.012	78.9	21.1
	30	0.6/1000	0.018	85.0	15.0
	40	0.6/1000	0.024	90.2	9.8
H_2SO_4 (13.8 micron)	20	2.5/1000(3)	0.050	92.8	7.2
	30	2.5/1000	0.075	95.5	4.5
	40	2.5/1000	0.100	96.2	3.8

TABLE 4-12B

PENETRATION TEST DATA FOR VARYING INLET DUST LOADING

Aerosol	W/G gal/1000 ft.^{3} of air	Inlet Dust Loading gr./ft.^{3}	$(C_d)(W/G)$	Weight Collection Efficiency %	Passage %
Fly Ash (14.3 micron)	30	0.02(4)	0.6	99.0	1.0
	30	1.60(1)	48.0	99.4	0.6
$CaCO_3$ (2.6 micron)	30	0.25(4)	7.5	88.2	11.8
	30	1.50(1)	45.0	93.4	6.6

(1) Harvard generator feeder
(2) Aspiration/Elutriation preparation
(3) Aspiration/Impingement preparation
(4) NBS feeder

FIGURE 4-14
SOLIVORE SCRUBBER
PENETRATION AS FUNCTION
OF
AGGLOMERATION INDEX, (C_d) (W/G)
DATA OF KRISTAL, ET AL (1957)

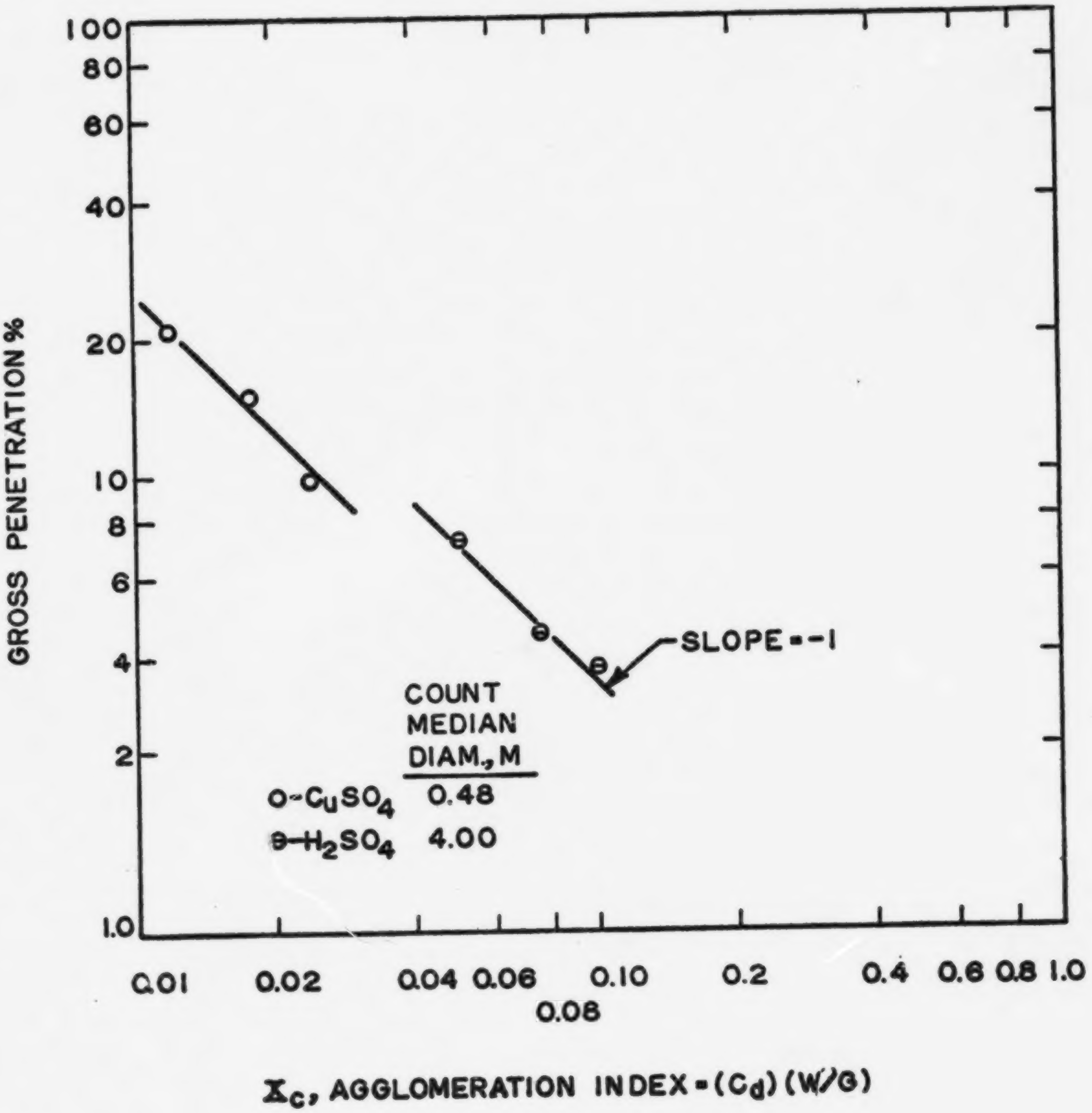
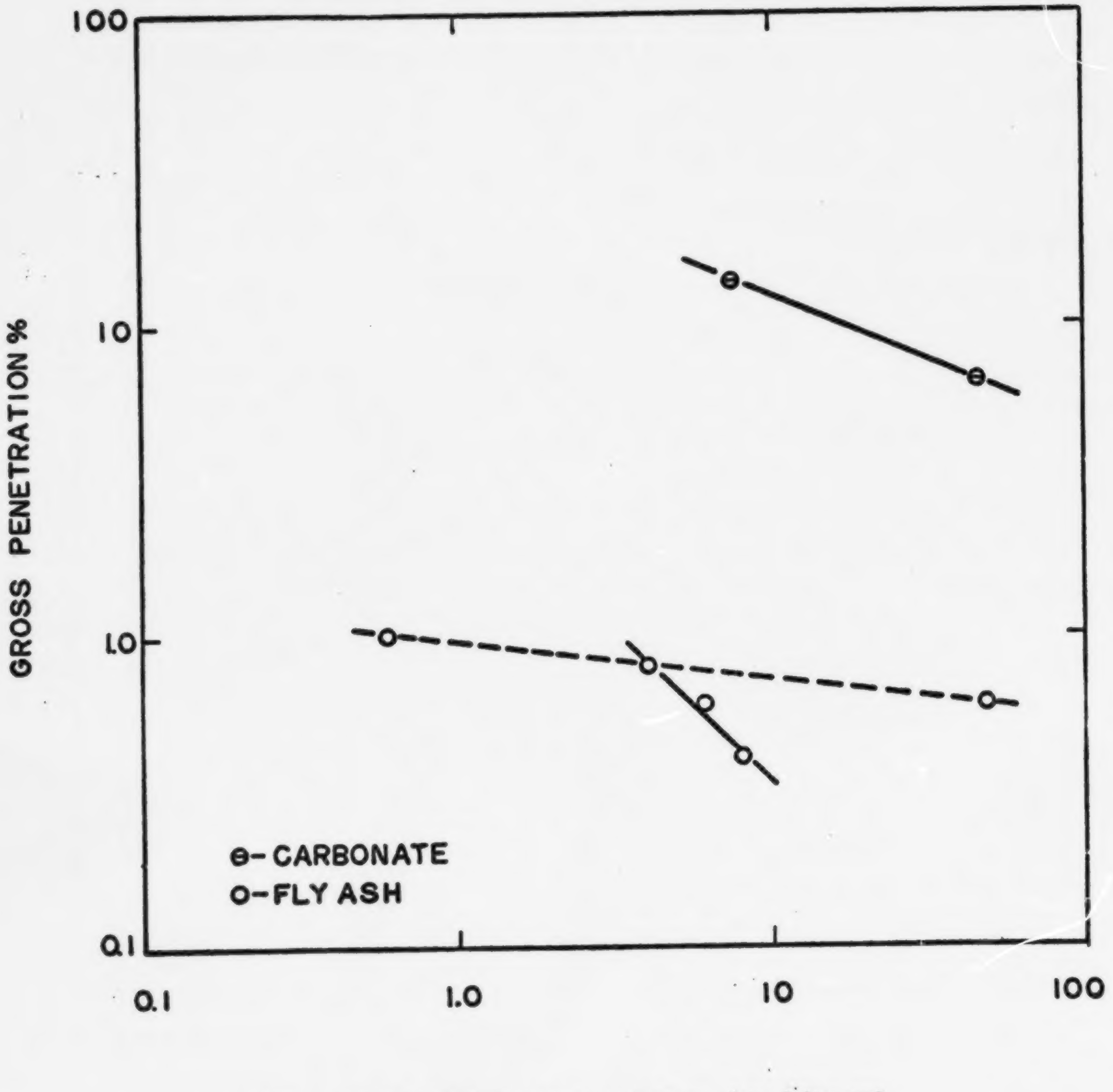


FIGURE 4-15
SOLIVORE SCRUBBER
PENETRATION AS FUNCTION OF AGGLOMERATION INDEX, (C_d) (W/G)
DATA OF KRISTAL, ET AL (1957)



The fly ash data of Figure 4-15 exhibit several obvious anomalies, in addition to any that may have been caused by feeder variation. The central three points, from Table 4-12A for the varying water rate series of runs, appear to fall on a -45° line, parallel to the other two run series in this sequence plotted in Figure 4-14, despite the difference in feeder type. However, when the varying inlet dust loading data of Table 4-12B are added, complete data disagreement results. The data point on an X_c value of 0.6 was obtained with the NBS dust feeder at a dust loading of 0.02 gr/CF, while the data point at X_c = 48, using the Harvard feeder, corresponds to a dust loading 80 times greater, or 1.60 gr/CF. In order for these points to be aligned with the -45° line drawn through the three central points, the penetration value at X_c = 0.6 would have to be 5.4% and that for X_c = 48, 0.07%. While pre-agglomeration prior to scrubber entry may effectively decrease the penetration from the anticipated 5.4% to the actual 1.0%, it cannot explain the increase in penetration from the expected 0.07% to the actual 0.6% at the other end of the line. There appears to be a probable explanation for this effect, however, in the analytical data provided by the authors and given in Table 4-13.

The use of a settling bottle in the effluent sampling line enabled the collection of wetted dust agglomerates which escaped collection in the scrubber, thus yielding the two sets of penetration values listed in Table 4-13. It was not stated whether the data of Tables 4-12A and 4-12B were given on a dry or wet basis, but the fly ash run of Table 4-13 corresponds to an X_c value of 4.5, and yields penetrations of 0.6% dry, and 1.6% wet. The dry value falls close to the -45° line of Figure 4-15, while the 1.6% penetration is higher than any of the other fly ash data points. The functional efficiency of a settling bottle in removing the wetted dust agglomerates is unknown, and it is probable that a fraction of the wetted-agglomerate reported to the dry sample, which could, at the sensitive low end of the penetration scale, easily account for the displacement of a penetration value from 0.07% (projected) to 0.60% (indicated). As discussed previously in terms of the data of Calvert and Legatski, the experimental difficulties in accurately determining penetration levels less than 1.0% undoubtedly contribute to the apparent discrepancy.

The appearance of wetted-dust agglomerates in the scrubber effluent samples for the Solivore runs parallels the behavior observed by Ingels for the multi-stage centrifugal

TABLE 4-13

EFFECT OF SAMPLING METHOD ON ESTIMATION OF EFFLUENT LOADING SINGLE-STAGE SOLIVORE SCRUBBER

DATA OF KRISTAL, DENNIS AND SILVERMAN (1957)

Aerosol	Inlet Loading gr./CF	Outlet Loadings Dry gr./CF	 Wetted gr./CF	 Total gr./CF	Efficiency Dry[(a)] %	 Wet[(b)] %
Fly Ash	0.15	0.0009	0.0015	0.0024	99.4	98.4
Talc	1.5	0.056	0.027	0.083	96.2	94.4
H_2SO_4 (coarse)	0.0025 mist(c)	0.00011	0.00027	0.00038	95.5	84.7

(a) "Dry" refers to dust passing settling bottle in sampling line.

(b) "Wet" refers to dust entrained in water droplets retained in settling bottle.

(c) No droplet eliminator in collector.

scrubber, discussed earlier. It is obvious that in both cases, the scrubbers are not doing an adequate job of removing the dust-water agglomerates formed, even though the agglomerate-formation contacting efficiency is high. The very fact that the contacting efficiency is high may impose too great a demand on the removal function of the unit. Inasmuch as the agglomeration index correlation approach assumes the removal from the gas phase of all agglomerates of a critical minimum size, data for equipment utilizing a separate positive mechanism for agglomerate removal, such as a venturi-cyclone combination, should correlate better than data for a unit providing inefficient removal. The latter defect in scrubber design will be evidenced by excessively high penetration levels at high X_c values, and the agglomeration index thus becomes a measure of the adequacy of the specific scrubber design function of agglomerate removal.

3. Size-Dependent Penetration Behavior

Because of the limitations of data availability, it is difficult to go beyond a speculative level of analysis of penetration dependence on particle size. Nevertheless there are a number of suggestive patterns of behavior in the penetration graphs presented to warrant preliminary discussion. In Figure 4-14 the agreement in penetration behavior on an agglomeration index plot between aerosols of widely different particle sizes raises some fundamental questions. The respective count median diameters of the $CuSO_4$ and H_2SO_4 microspheres were 0.48 and 4.0 microns, so that, on a population basis, there were roughly 10 times as many $CuSO_4$ particles per unit volume as there were H_2SO_4 mist droplets, at equal C_d levels.

If agglomeration with water drops or self-agglomeration of the dust to critical removal size is particle population-dependent, as all of the experimental data indicate, then the fractional penetration of the $CuSO_4$ aerosol should be substantially lower than that of the H_2SO_4 mist at the same run conditions. However, if the limited data of Figure 4-14 are truly representative, the performance of the scrubber for $CuSO_4$ is substantially identical to that for H_2SO_4. There are several explanations for this behavior. On the basis of conventional impaction theory, the target efficiency of the water drops for the smaller-size fractions of the $CuSO_4$ aerosol is probably negligible, and certainly less than for the H_2SO_4, which would tend to offset the effect of the higher particle number concentration. Thus, the agreement of the penetration behavior of the two aerosols may be regarded as fortuitous, resulting from a coincidental balance of opposing capture forces.

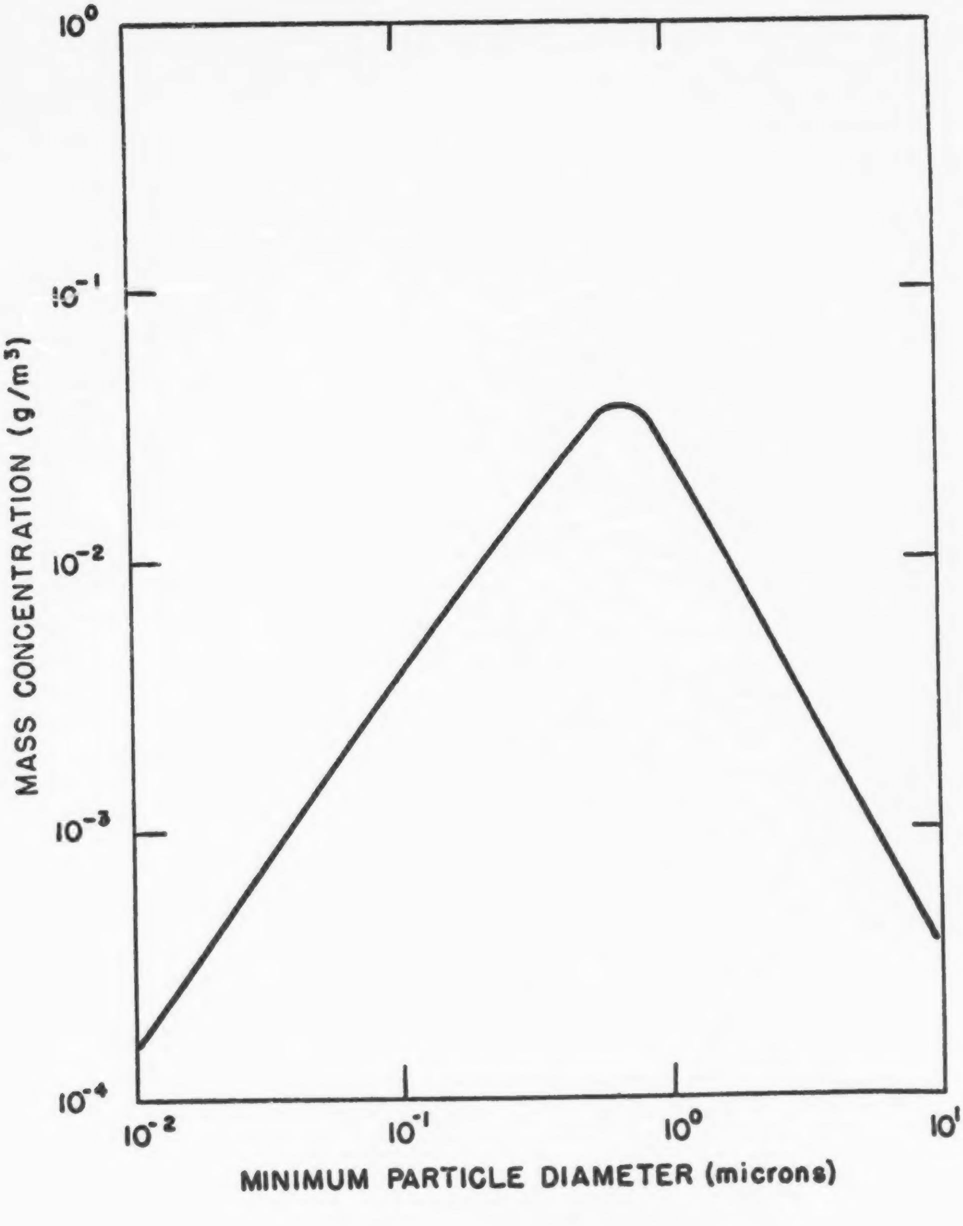
An alternate explanation, and one with fundamental significance, is afforded by the recent work of Davis and Truitt (1971). These investigators calculated atmospheric aerosol concentration as a function of size distribution for a steady-state aerosol injection rate in balance with a turbulent-mixing "coagulation" and gravitational fallout rate. It will be noted that this is essentially the same general mechanistic scheme proposed as the basis for scrubber operation in this report. In their work, Davis and Truitt assumed an input particle mass distribution in accordance with Equation (4-4), with limits of D_{max}=100 microns, and D_{min} as the independent variable, ranging from 0.01 to 10 microns. For the assumed values of D_{min}, the steady-state airborne concentrations were calculated for removal by coagulation and settling, with the results given by Figure 4-16. The highest steady-state concentration was found to result from minimum particle diameters of 0.2 to 2 microns.

If the analogy can be fully drawn between the Davis and Truitt atmospheric fallout model and the action of a wet scrubber on an accelerated time-scale, then the residual dust penetration (equivalent to the steady-state airborne concentration) would be a function primarily of the minimum particle size, assuming the mass-size distribution of Equation (4-4) and a fixed D_{max}. Qualitatively, the shape of Figure 4-16 was explained by Davis and Truitt in a manner that would also apply to wet scrubber action. If the minimum particle size is relatively large, say, greater than 2 microns, then all of the particles are readily removed, and penetration would be quite low. This situation corresponds to the scrubber case where agglomeration action is not necessary, and the agglomerate-removal mechanism in and of itself is sufficient for efficient operation. Alternately, if the minimum particle size is quite small, say, less than 0.2 micron, then the number concentration is very high and the agglomeration (coagulation) rate is high enough to yield rapid formation of particles greater in size than the critical removal size. In other words, for small particles, agglomeration governs, while for large particles, the removal mechanism controls penetration. The intermediate particle size range, which for Figure 4-16 would be 0.2 to 2 micron, constitutes the most stable or difficultly-removable size fraction for the atmospheric holdup problem.

With reference to the atmospheric particle stability problem, the comment of Davis and Truitt regarding the stable size range is of pertinence here: "So in summary, the particle

FIGURE 4-16

STEADY-STATE AEROSOL CONCENTRATION
vs. MINIMUM PARTICLE SIZE
DATA OF DAVIS & TRUITT (1971)



size range (perhaps roughly 0.2-2 micron diameter) constitutes the worst of particulate air pollution. These are the particles that get deposited in the lungs; these are the particles that cause reduced visibility; these are the particles that settle slowly and have a long airborne life. Indeed, it appears that particulate air pollution could well be defined as the 0.2-2 micron particles."

Some rather remarkable prior experimental confirmation of the Davis and Truitt theoretical treatment is given by the study of Langstroth and Gillespie (1947) of coagulation and surface losses of smokes in still and turbulent air. Results of the particle size distribution studies on ammonium chloride smoke showed that in still air, the coagulation and fallout sequence gave a stable residual particle size of 0.8 to 1.2 micron, from the smoke having an initial size frequency peak in the 0.01 to 0.2 micron range. Turbulent or stirred air gave a stable size frequency peak corresponding to the 0.05 to 1.0 micron range. However, in the latter case, the size-frequency peak shifted with time from a value of about 0.03 microns at 100 minutes to 0.07 microns at 280 minutes indicating the accelerative effect of turbulence on coagulation. The similarity between the experimental curves of Langstroth and Gillespie and the theoretical curve of Davis and Truitt in Figure 4-16 is quite striking, and the possible significance of these data to wet scrubber work is worth exploring.

The question here arises as to what extent turbulent coagulation-fallout theory actually applies to wet scrubber performance. The preliminary indications given by the agglomeration-index correlation work of this design review are that wet scrubbers may very well obey the same rules applying to the more extended time-scale atmospheric dust separation phenomena, and coagulation-removal theory may afford a better explanation for scrubber data than impaction theory. Certainly, the assumption that wet scrubbers are merely accelerated time-scale turbulent mixing devices yielding the same results as the atmospheric process serves to explain some well-known and seemingly anomalous scrubber characteristics. For example, it has been shown by Kristal, Dennis and Silverman (1957) among others, that for several scrubbers or scrubbing stages in series, penetration will follow the log-penetration law:

$$E_T = 1 - (1 - E_o)^n \qquad (4\text{-}5)$$

$$= 1 - (F_o)^n \qquad (4\text{-}6)$$

where

E_T = overall scrubber efficiency, fractional

E_o = stage efficiency, constant

F_o = penetration of a single stage

n = number of stages

Equation (4-5) properly applies only to the collection of uniform aerosols, and as Kristal et al notes, "in order for the second and third stage of the experimental collector to be as efficient as the first stage, the effluent from any preceding stage must have undergone sufficient conditioning (through agglomeration, particle and water contact, and possibly condensation) to approach the size distribution of the original aerosol. In the absence of particle conditioning, multi-stage operation would ordinarily be impractical". The fact that the experimental data for multi-stage scrubber collection follows the log-penetration statement of Equation (4-5) has been difficult to reconcile with the concomittant necessity of accepting constancy of particle size distribution, as per first stage, throughout the equipment, despite the removal of 98% or more by weight of the aerosol. It is obvious that Figure 4-16, and the supporting turbulent-agglomeration atmospheric fallout theory, supplies the answer. Given the difference in turbulent mixing intensity, residence time and removal mechanism of wet scrubbers, the stable size fraction is probably higher than that shown in Figure 4-16, and literature data suggest that it may lie in the 2 to 20 micron range. Nevertheless, turbulent agglomeration and surface or inertial removal in the first stage should produce a "stable" size distribution within that stage which should persist in stability throughout all stages as long as the mechanisms of agglomerative contacting and agglomerate removal remain the same. While the constancy of particle size distribution through repetitive scrubbing stages may be difficult to accept, this behavior has been unavoidably inherent in the experimentally-verified log-penetration law behavior of multi-stage units.

A further insight is provided by the observation of Langstroth and Gillespie (1947) that the rate of coagulation depends on the square of the number of particles, while the rate of sedimentation (or inertial removal) depends on the first power of the particle concentration. This suggests that it would be possible to test a scrubber for primary function by making a series of varying concentration runs at several fixed particle size distribution, and determining the relation between penetration and particle concentration. This is essentially what was done in some of the dry runs reported by Calvert and Legatski, and the dependence of penetration on the -1 power of C_d for such units as the Multiclone and packed tower would indicate that these are non-agglomerating, pure inertial removal devices. It should also be pointed out that the agglomeration index treatment for wet scrubbers is predicated on the product of the water drop and dust particle concentration terms (replacing the square of dry dust concentration) and assumes that dust-dust collisions do not contribute significantly to agglomeration. All of the assumptions and findings of this report are subject to direct testing in the context postulated, and such a program is obviously indicated. In the meantime, it is informative to review additional data which does not fit the relationships previously established for penetration behavior in wet scrubbers.

F. ANOMALOUS BEHAVIOR

In addition to the above-noted Kristal et al (1957) data on $CaCO_3$ and fly ash, and the fly ash data of Johnson (1955) reviewed earlier, departure from the expected inverse relationship between penetration and dust loadings, or the agglomeration index, is observed in the data of Lapple and Kamack (1955) and Lancaster and Strauss (1971).

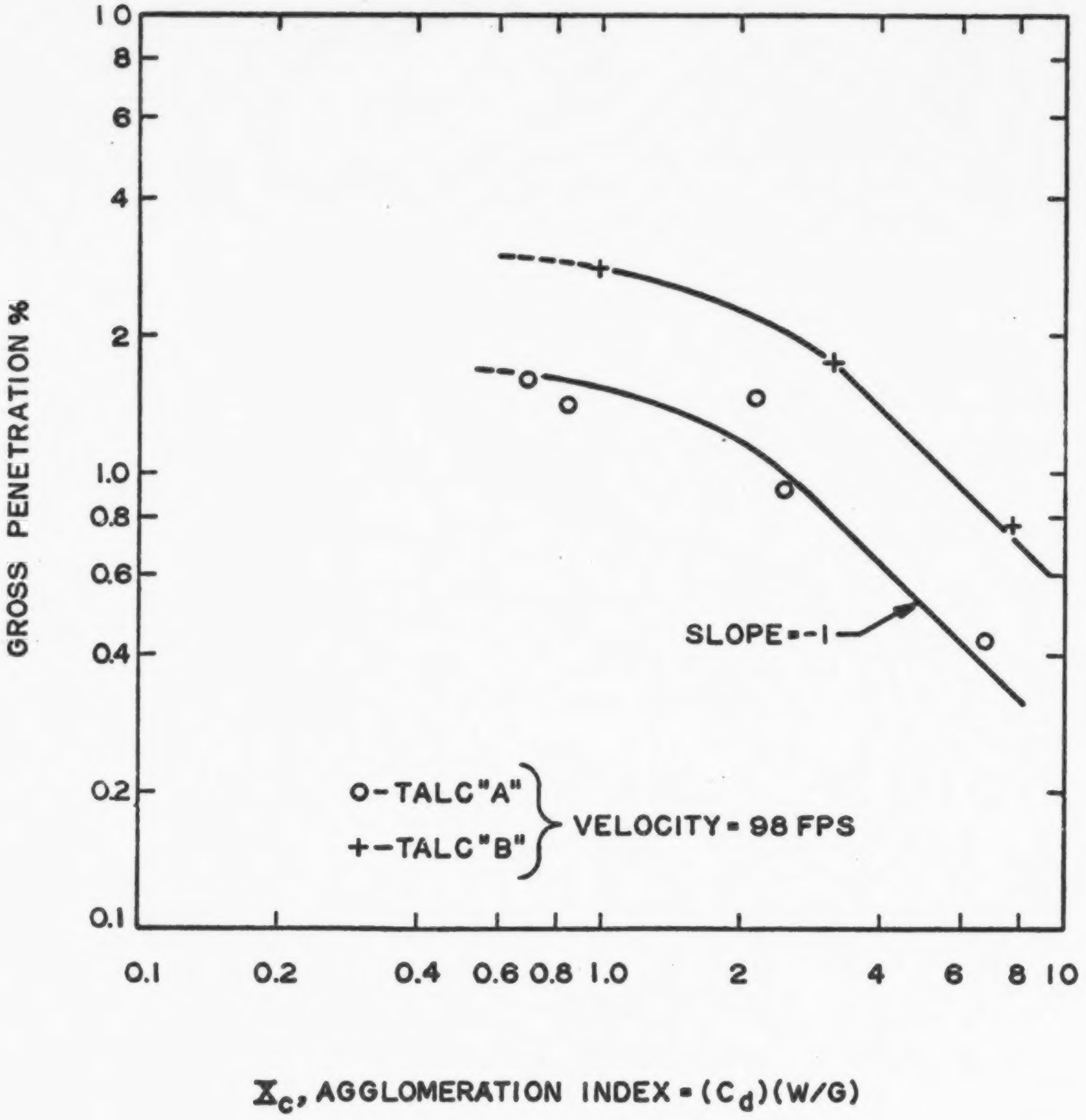
1. Data of Lapple and Kamack (1955)

The experimental studies reported by Lapple and Kamack covered performance tests on the effect of operating variables on the efficiency of several laboratory and semi-works scale scrubbers. The important variables were indicated to be inlet dust loading, water/gas ratio, gas velocity and/or pressure drop. While the authors' final conclusion was that contacting efficiency, at constant inlet dust loading, is solely a function of the total gas power input (degree of turbulent mixing) the effect of varying (W/G) ratio on penetration was shown only by independent points for this variable, and cross-correlation was not attempted. Replotting the Lapple and Kamack data on a $(C_d)(W/G)$ basis, rather than dust loading alone, eliminates the effect of varying (W/G) and results in a single series of constant-gas velocity lines for each scrubber. However, the data are limited and not very consistent, with the slopes of the penetration vs. agglomeration index lines varying from -0.1 to -1.0.

The erratic behavior of their penetration-dust loading plots was noted by Lapple and Kamack, and explained on the basis of pre-agglomeration of the dust, and directly attributed to "a failure of the dispersing venturi to disperse completely the bulk dust". This effect was particularly apparent for the ilmenite and titanium oxide tests dusts, and much less so for the two talc dusts used. Although only two points were presented for the specific low dust concentration region, the authors indicated that the penetration approached a "constant value" for dust loadings less than 2 gr/CF, but decreased rapidly at loadings above 10 gr/CF. Actually, this pattern is occasionally quite evident in an agglomeration-index treatment of their data, such as Figure 4-17. The explanation advanced by Lapple and Kamack for this effect of dust loading was that "the dust present at high concentration is effectively coarser because of agglomeration than the same dust at low concentration", even though the particles were statistically 20 to 80 diameters apart at the higher concentrations.

This argument that the degree of pre-agglomeration is concentration-dependent is refuted by the data of Ingels and of Calvert and Legatski reviewed earlier. The latter test systems contained a preliminary inertial separator between the dust source and the test scrubber. This type of arrangement serves to remove the agglomerates formed by the dispersing unit, or which remain undispersed from the bulk dust, and yet tests carried out under these conditions clearly show a constant penetration/dust loading relationship which is invariant with dust concentration range. Thus, the Lapple-Kamack hypothesis of pre-agglomeration in the feed dust only at the higher concentrations does not appear to be supportable. In fact, the more likely explanation is the reversal of that advanced: pre-agglomeration causes the flattening of the curve of Figure 4-17 in the low C_d range, rather than the high C_d range. As stated earlier, if pre-agglomerated material is fed to the scrubber, then the apparent efficiency will be higher than that to be expected if the same dust loading consisted of completely dispersed particles. The agglomeration function normally required of the scrubber has already been partially performed, and the test is really of the scrubber agglomerate-removal function. Thus, penetration will be lower than normal, with resulting depression of the usual curve. The fact that the curve increases in negative slope with increasing dust loading, approaching the normal -1 value, indicates either that the turbulent-mixing mechanism of the scrubber is causing additional re-dispersion of the dry-dust agglomerates, or that the fraction of pre-agglomerated material diminishes at the higher concentrations.

FIGURE 4-17
PERFORMANCE OF 1-INCH S-BEND CONTACTOR AND 8-INCH CYCLONE IN SERIES
PENETRATION AS FUNCTION OF AGGLOMERATION INDEX
DATA OF LAPPLE & KAMACK (1955)



2. Data of Lancaster and Strauss (1971)

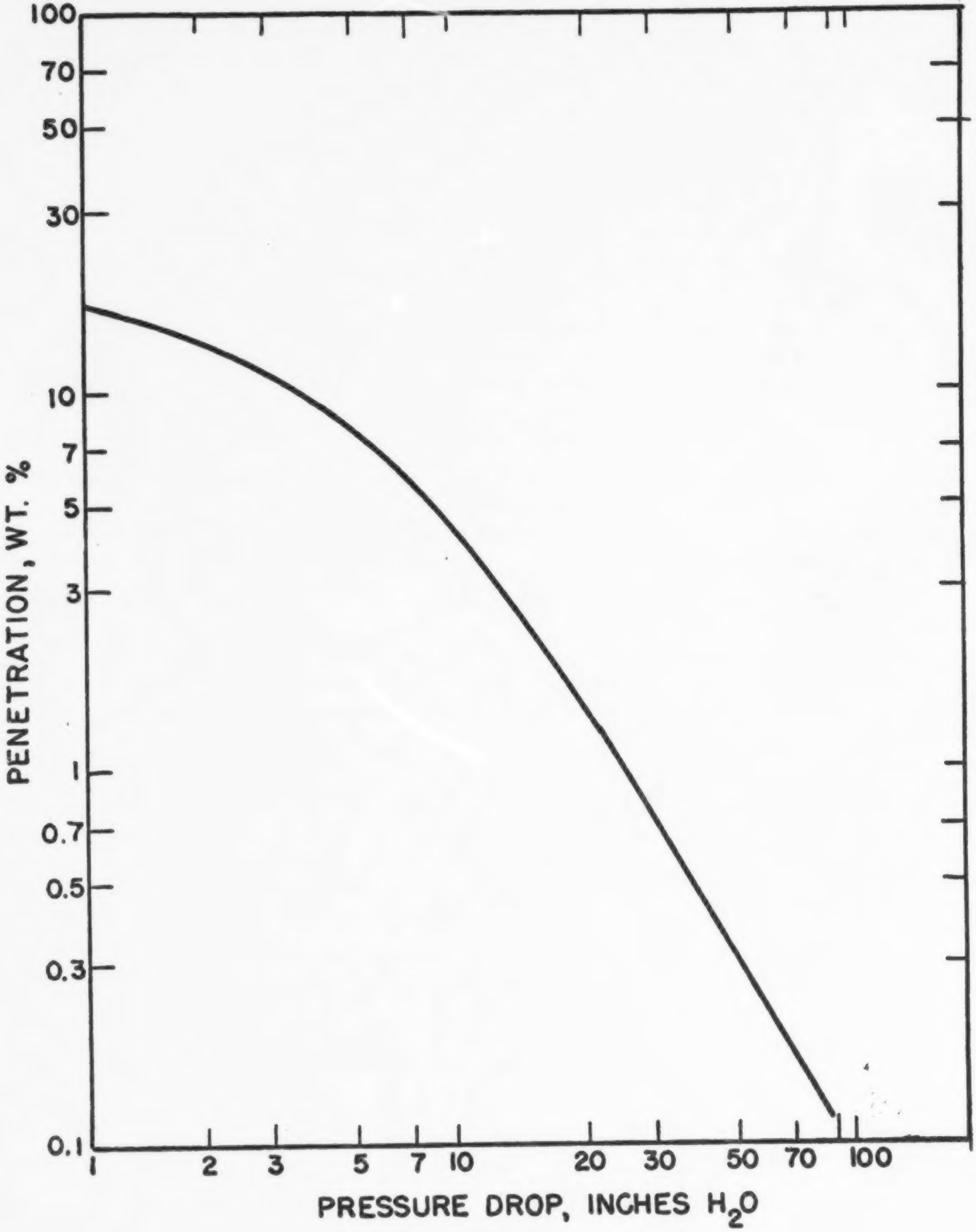
The influence of the pre-agglomeration effect on scrubber performance is still occasionally unrecognized. The recent study of Lancaster and Strauss (1971) on the influence of steam injection in a wet cyclone scrubber presents a series of penetration-loading curves which are remarkably similar to Figure 4-17, even with respect to the loading range of 2 to 5 gr/CF at which the curves "bend" toward a slope of -1. These curves are for runs both with and without steam injection, so that the effect is characteristic of the feed/scrubber system. Inspection of the test setup for this study shows that the "Harvard generator" and "dispersing" venturi arrangement was used, and it is apparent that these data suffer from the acknowledged deficiency of the Lapple and Kamack data, that of feed pre-agglomeration. It is unfortunate that this fundamental anomaly continues to be introduced into scrubber test work, inasmuch as it is quite obvious that without this invalidating factor, performance and design correlation efforts would be much further advanced than they are at present.

G. PENETRATION AS A FUNCTION OF SCRUBBER PRESSURE LOSS

The third primary scrubber variable indicated by the literature on scrubber performance is the gas velocity or pressure drop. Lapple and Kamack made extensive measurements of the effect of this variable on penetration (unfortunately at various levels of feed pre-agglomeration) and concluded that the "controlling factor in scrubber performance must be one associated with pressure drop. Such a factor is turbulence". Unlike the apparently simple relation of gross particulate penetration to the other two primary scrubber variables of dust and water drop concentrations, the effect of pressure loss on penetration is complex. On the basis of the turbulent agglomeration mechanism which appears to govern the observed wet scrubber behavior, it would be expected that there would be two different zones of penetration dependency on gas flow, corresponding to (a) laminar flow and (b) fully-developed turbulent flow. This is approximately the behavior observed in full-range flow experiments on wet scrubbers.

The most complete data on pressure drop are those of Lapple and Kamack, and a typical curve for penetration as a function of scrubber ΔP is given in Figure 4-18 for the Venturi orifice or cyclone scrubber. In general, the typical curve consisted of three regions: a low ΔP region of less

FIGURE 4-18
TYPICAL BEHAVIOR OF PENETRATION AS FUNCTION OF PRESSURE DROP
DATA OF LAPPLE & KAMACK (1955)



than 7" W.C., where the log-log penetration/ΔP plot had a slope of about -0.5, a high ΔP region above 15" W.C., where the slope was approximately -1.8, and an intermediate zone from 7 to 15" ΔP connecting the low and high ΔP regions. This zone may either be drawn as a curved segment, or a straight line of -1 slope. This curve was obtained for all dispersed-water contactors tested except for the cases of the sieve tray, dry runs, or for seriously pre-agglomerated feed dusts. The mode of water introduction and its initial degree of dispersion had only a small effect on the relative position of the dust loss/ΔP curve, and, aside from the exceptions noted, the type of contactor did not cause a major shift in curve location.

The standard sieve tray runs produced a straight-line penetration/ΔP relationship, with a slope of -0.75, confirming the finding of the Calvert and Legatski data that this unit does not utilize the normal dispersed-water contacting mechanism. The pre-agglomeration effects in the ilmenite and titanium dioxide runs on the standard penetration plots were drastic, with increases in penetration occuring with increasing velocity (ΔP). By manipulation of the water rate and equipment type, it was possible to obtain a limited amount of varying ΔP data at constant inlet velocity conditions for these problem dusts, and these data gave normal plots of the type shown in Figure 4-18. However, these constant-velocity curves are displaced to the right with increasing gas velocity, and it is uncertain whether this effect is the result of a more complete degree of dispersion of the entering feed dust or a separate secondary effect of gas velocity in water atomization. It was visually observed that, for the Venturi and pipeline scrubbers, a marked improvement in the degree of water atomization took place as the pressure drop approached and exceeded 15" W.C., but Lapple and Kamack considered this to be a minor secondary effect, and indicated that the level of gas turbulence controlled. Again, it should be noted that, without the pre-agglomeration complication, it would have been farily simple to separate and identify the effect of water atomization as a function of gas velocity by means of the constant velocity-varying ΔP runs.

The linearity of fractional dust penetration with ΔP above 15" W.C. obviously enables a complete and simple statement of the relation of penetration to the three primary variables for this range:

$$F = \frac{K(\Delta P)^{-1.8}}{(C_d)(W/G)} \qquad (4\text{-}7)$$

where K is a performance constant, characteristic of the scrubber and the sum of the secondary design variable contributions. However, even if data are obtained below the linear high ΔP range of Figure 4-18, knowledge of the full-range behavior facilities interpretation and understanding of the penetration results. A case in point is the work of Byrd and Dewey (1957) on application of a Venturi scrubber to the removal of odor attendant on the emission of submicron product fines and liquid aerosols. The Byrd and Dewey data were presented as smoothed-curve plots of percent odor removal and Venturi pressure drop as functions of (W/G), for constant parametric values of gas velocity through the Venturi throat. By cross-plotting these data, it is possible to obtain graphs of percent odor penetration vs. scrubber ΔP at constant gas velocity, and the Byrd and Dewey data are presented in this form in Figure 4-19. Although subjectively measured by panel testing, the "quantitative" odor penetration data appear to follow the same type of ΔP curve established by Lapple and Kamack for the dry particulates. While the data of Figure 4-19 are indirect, and are interpolated from the original smoothed curves, they do provide some insight into the probable separate effects of gas turbulence and water dispersion.

As shown in Figure 4-19, the Byrd and Dewey data fell into two groups, depending on the range of the gas velocity. The upper curve of Figure 4-19 covers gas velocities to 218 ft/sec, and this group of points form a line that is consistent with the behavior of the Lapple and Kamack data of Figure 4-18, although the range of ΔP is limited to 17" W.C. However, the group of data points corresponding to Venturi throat velocities of 242 to 338 ft/sec appear to fall on a separate curve of considerably lower (about one-third less) penetration levels. These data definitely indicate a separate effect of gas velocity on water atomization, in addition to the turbulent-mixing gas velocity effect directly measured by ΔP. Further, the apparently "critical" gas velocity classifying the data into two groups corresponds to the critical range of gas velocities above which water drops will shatter, approximately 200 ft/sec. Above this minimum, the drop size is controlled by gas velocity-induced atomization, and the drop size produced in a Venturi is given by the empirical equation of Nukiyama and Tanasawa (1938), which for water systems can be stated (Johnstone, 1949) as:

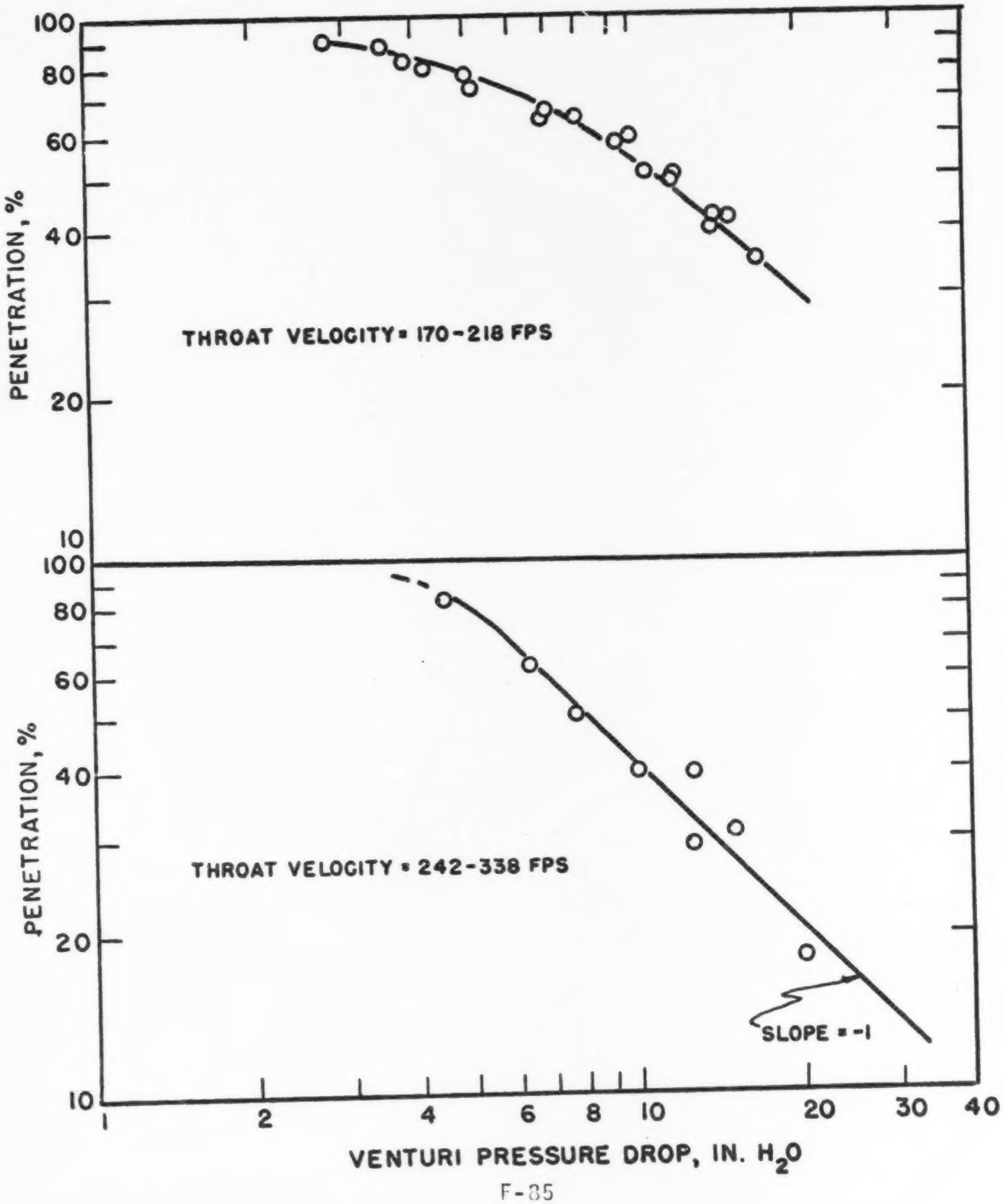
$$D_o = 16{,}000/\overline{V}_g + 1.4(W/G)^{1.5} \qquad (4\text{-}8)$$

FIGURE 4-19

VENTURI REMOVAL OF ODOR

PENETRATION AS FUNCTION OF PRESSURE DROP

DATA OF BYRD & DEWEY (1957)



where

D_o = mean Sauter drop size, microns

$\overline{V}_g$ = relative air-water drop velocity, ft/sec

As indicated by Equation (4-8), drop size, and therefore drop population, becomes gas velocity-dependent in the plus-200 ft/sec range, and secondary dependencies on (W/G) and V_g are introduced. The behavior of the Byrd and Dewey data is thus in accord with established dispersion effects for Venturi scrubbers, and because of the absence of any pre-agglomeration effects for this data (a pre-cyclone scrubber was used) it is probable that the Figure 4-19 separation by velocity range is a more accurate description of Venturi penetration performance than Figure 4-18. While Figure 4-19 does show self-classification of the penetration data into pre-critical and above-critical gas velocity ranges, insufficient data are available in the above-critical zone to permit differentiation of the velocity lines in accordance with Equation (4-8). The additional (W/G) dependency introduced by the drop-shattering phenomenon is a relatively small correction to D_o in the 200-400 ft/sec velocity zone, and would not be significant at values of (W/G) less than 10 gal/MCF.

The data of Figures 4-18 and 4-19 conceal some inherent contradictions which are well worth analyzing in conjunction with the use of Equations (4-7) and (4-8). The slopes of the sets of velocity lines in Figure 4-19 are substantially -1 in the range above 7" W.C. This is essentially the behavior of the Lapple and Kamack data of Figure 4-18 for the 7" to 15" ΔP range, and this indicates that penetration is inversely proportional to the ΔP of the scrubber. If, as Lapple and Kamack concluded, and as the data reviewed in this report have demonstrated, penetration is controlled by the degree of gas turbulence, then penetration should be inversely proportional to ΔP throughout the range of fully-developed turbulence including the +20" region. However, Figures 4-18 and 4-19 show that the -1 relation exists only up to about 15" to 20" W.C. ΔP, and then fairly abruptly breaks off to the -1.8 slope. Ignoring for the moment the additional ΔP effect that can be attributed to incremental liquid holdup and flow resistance caused by increases in (W/G), the most likely explanation of the increased slope of the penetration/ΔP plot in this range is that the efficiency increases because of the incremental effect of water atomization at this increased turbulence level. Equation (4-8) states that the mean drop diameter is inversely proportional to the gas velocity (square root of ΔP) at constant (W/G) levels, and if water droppopulation number is inversely proportional to the cube of the drop diameter, then as a first approximation:

$$N = (k/D_0)^3 = (k'V_g)^3 \qquad (4\text{-}9)$$

$$= k''(\Delta P)^{1.5} \qquad (4\text{-}10)$$

where

N = water drop population concentration

Equation (4-10) indicates that penetration should be inversely proportional to $(\Delta P)^{2.5}$ in the water atomization region, rather than the 1.8 power shown in Figure 4-18. However, in Equation (4-9) the correct drop diameter required is the count mean diameter rather than the Sauter mean drop diameter, so that more properly, the slope of the ΔP line in the +15" W.C. region in Figure 4-18 should only be expected to be in the -1 to -2.5 range. Conversely, the increment of -0.8 in the slope actually obtained as a result of water atomization would call for re-writing Equation (4-10) as:

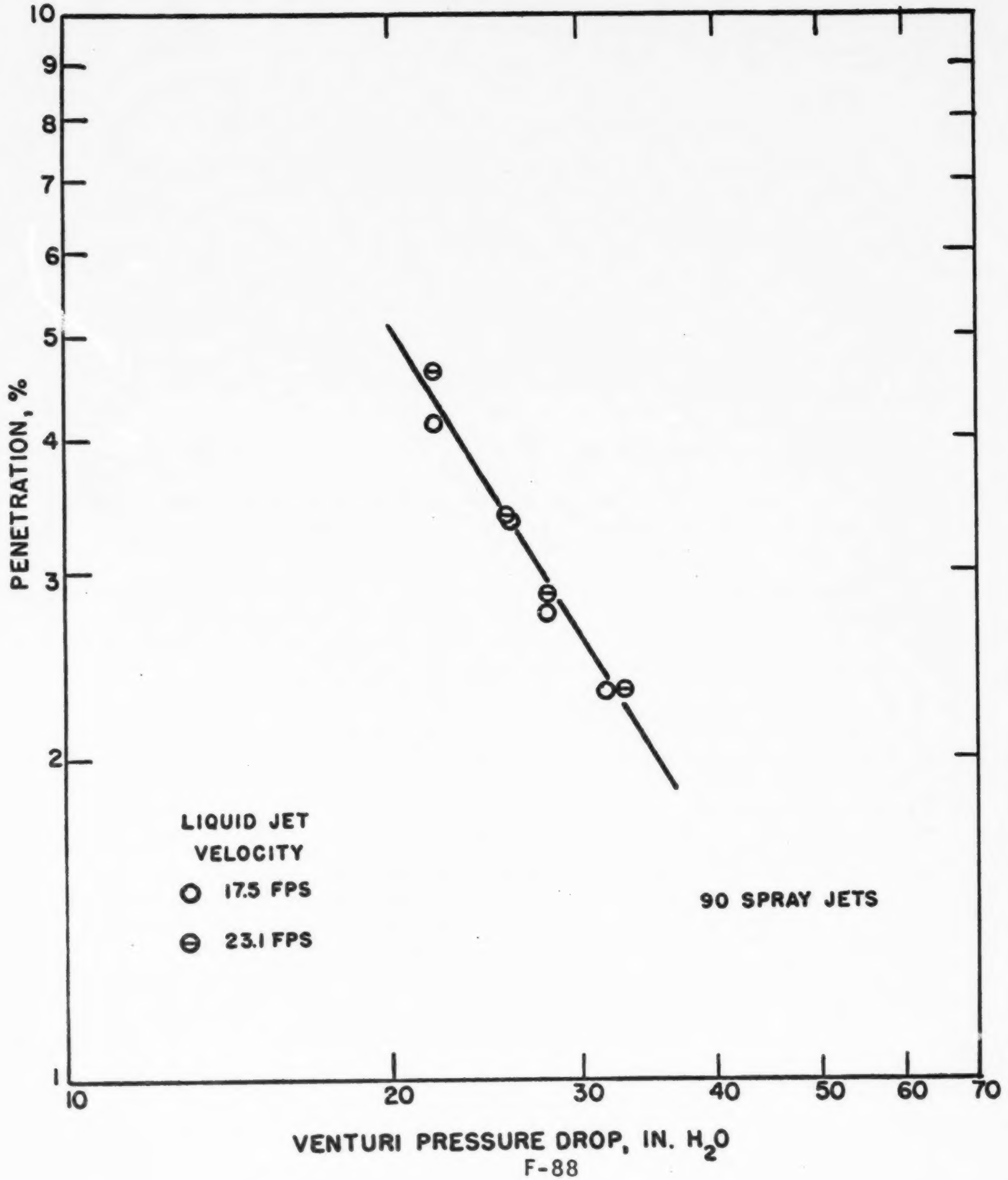
$$N = k''(\Delta P)^{0.8} \qquad (4\text{-}11)$$

The limited range of ΔP in the Byrd and Dewey data do not permit examination of the validity of Equation (4-11) for the water atomization region, but additional information on the high-range penetration/ΔP behavior in a Venturi scrubber is provided by the work of Brink and Contant (1958) on scrubbing of phosphoric acid mist. Mist loadings were held constant at 1400 mg/CF of P_2O_5, and factorial design of the experiments enabled studies of the individual variables of spray liquid rate, throat gas velocity, liquid injection velocity, and total number of spray jets. The water jet spray velocity was found to significantly influence the performance of the Venturi, with velocities greater than 25 ft/sec yielding higher penetrations. In replotting the Brink and Contant data, it was found that using the higher spray velocity data of 30 and 40 ft/sec produced scatter and generally higher penetration values than were characteristic of the low-velocity jet runs, and accordingly, log-log penetration/ΔP plots were made only for the latter data. A typical plot of the Brink and Contant data is presented in Figure 4-20 for percent penetration vs. overall scrubber pressure drop for an injection rate of 150 GPM. A straight line with a slope of -2.0 is obtained from the data, and it should be noted that the ΔP range is 20-40" W.C. This latter range corresponds to the high-ΔP segment

FIGURE 4-20

VENTURI REMOVAL OF PHOSPHORIC ACID PENETRATION AS FUNCTION OF PRESSURE DROP

DATA OF BRINK & CONTANT (1958)



of the Lapple and Kamack curve of Figure 4-18, and the agreement between the -2.0 and -1.8 slope values may be considered to be fairly good.

Plotting additional Brink and Contant data at an injection rate of 200 GPM gave a line parallel to that of Figure 4-20, but at the expected lower penetrations. It was believed that the water jet velocity effect caused by transverse injection noted by Brink and Contant was due to a momentum exchange which effectively lowered the relative gas velocity. If such was the case, then at constant water jet velocity, the initially higher penetration observed at the superficial velocity as measured by the ΔP should decrease with increasing ΔP. This was confirmed by several of the graphs made for the high-velocity jet runs, which showed curved lines approaching the "normal" low-velocity jet line at the high ΔP values, but data scatter was too great to generalize this effect.

The analysis presented above considers penetration to be inversely proportional to both the degree of turbulent mixing and the population concentration of the water drops (at constant C_d). The agglomeration, or dust-water collision concept, postulates that the intensity of gas turbulence and population concentration of water droplets are separate and independent primary variables. Inasmuch as each of these two variables is individually dependent on the first power of ΔP in the drop-shattering range, the concept qualitatively describes the observed ΔP behavior of wet-scrubbers. Additionally, below the critical range of gas velocities which cause drop-shattering, the penetration should be dependent on the -1 power of ΔP, rather than the -2 power of the higher ΔP range, and again, the observed behavior is in accord with these expectations.

There is reason to suspect that, in terms of ΔP behavior, Venturi scrubbers may show characteristics not exhibited by other wet scrubbers. As Winklepleck (1970) has shown, for the Venturi, a conservation of energy balance yields an expression for scrubber pressure drop in terms of gas velocity, gas density, and liquid injection rates:

$$\Delta P = V_g^2[A\rho_g + B(W/G)] \qquad (4\text{-}12)$$

where

A, B = constants

Thus, a given ΔP may be obtained by adjusting either the gas velocity or liquid rate, and there will be an infinite number of combinations of these latter variables providing the given ΔP. Equation (4-12) indicates that it may be more rational to work from a velocity and liquid/gas ratio base toward an efficiency correlation for Venturi units, but such separate data are seldom available.

It is obvious that, while the turbulent-agglomeration approach is rational and empirically productive, it lacks an adequate supporting theoretical base. Thus, one of the prime objectives of any research and development program based on the correlation of this report should be the development of a consistent theory.

V. CORRELATION IN SEARCH OF A THEORY

The agglomeration-index correlation presented in Section 4 has been empirically-derived, but it has the singular advantage of fitting wet scrubber experimental and field data. Anomalous data that do not follow the correlation are readily accountable in terms of known inherent deficiencies in either the test methods or the scrubber itself. The final correlating equation:

$$F = \frac{K(\Delta P)^{-n}}{(C_d)(W/G)} \qquad (5\text{-}1)$$

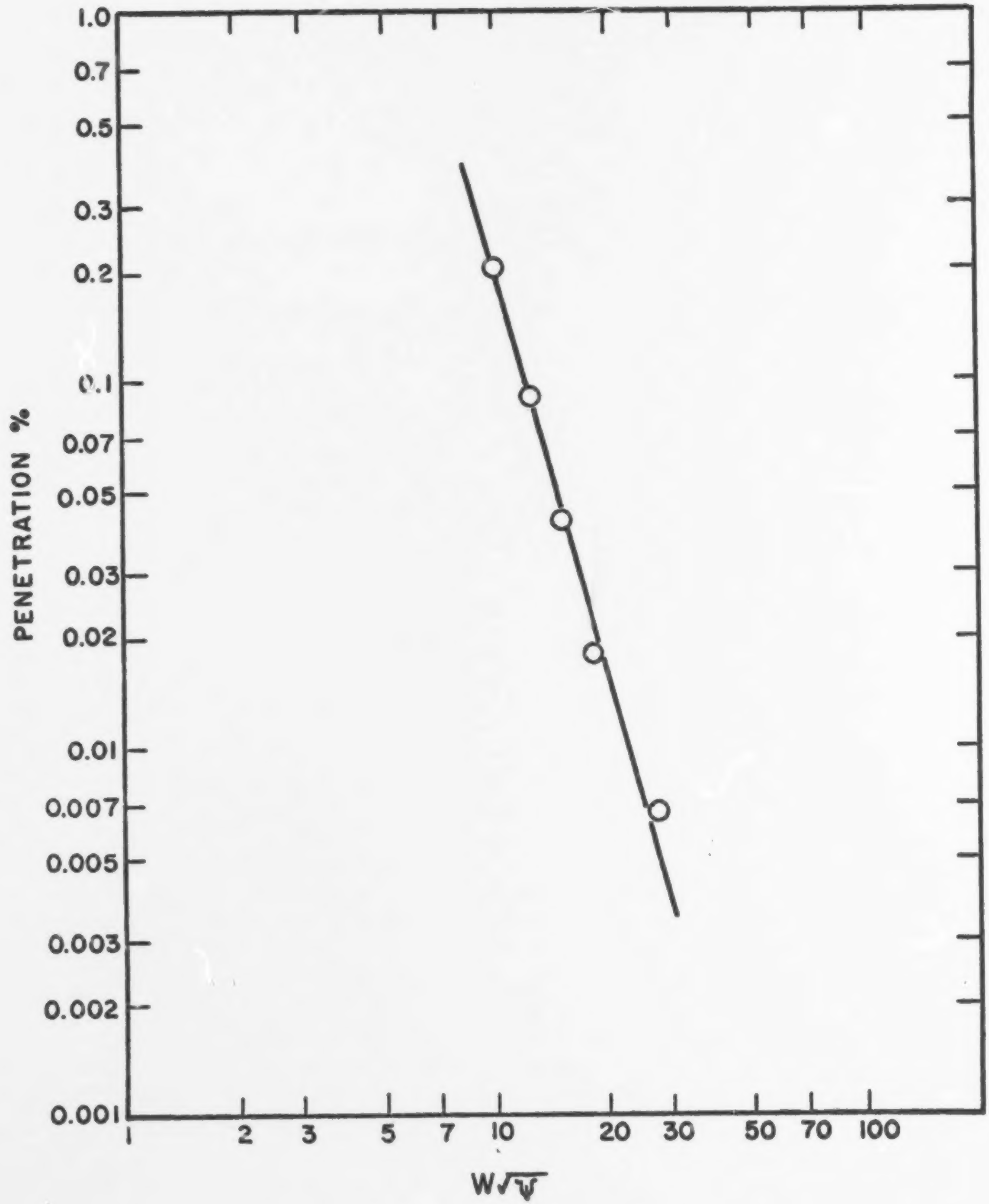
where n = integer of 1 or 2, depending on ΔP regime

is usable in its present form both for scrubber performance correlation and for design. Equation (5-1) allows, for the first time, valid and absolute performance comparisons between scrubbers of different types, and establishes the ground-rules for parameter constancy which must be observed to validate such comparisons. It further provides a basis for direct parametric testing and research on wet scrubbers, and the need for programs of investigation of the effect of particle mass and number distribution and other variables in context has already been noted. The one definite and acute deficiency is the present lack of a theoretical base, which persists despite several preliminary attempts at reconciliation of inertial impaction theory with the data treatment of the correlation approach. It has gradually been realized that not only does impaction theory fail to support the empirical correlation of this report, it vails to correctly describe fundamental wet scrubber behavior itself.

All of the correlations derived have consistently indicated that penetration correlates with such variables as (W/G), ΔP, and C_d on log-log plots. On the other hand, impaction theory calls for a semi-log relationship between penetration and W/G (or ΔP) and obviously only one of the two possibilities can be correct. A search of the literature showed that a direct experimental data test of the semi-log relationship between penetration and $(W/G)(\Psi)^{1/2}$, as a function of particle size was made by Brink and Contant (1958) and Johnstone, Feild and Tassler (1954) who produced a "linear" function for their data on such coordinates. However, even a casual inspection of the original plots shows a pronounced misfit of the experimental points, which exhibit a distinct curvature despite the imposed straight line. The Brink and Contant data have been replotted on log-log coordinates and are presented in Figure 5-1.

FIGURE 5-1

PENETRATION AS FUNCTION OF MODIFIED INERTIAL PARAMETER DATA OF BRINK & CONTANT (1958)



The fit of the data points to the straight line of Figure 5-1 is far better than in the original semi-log coordinate plot, and is consistent with the behavior of other (W/G) data examined in this report, except for the higher slope of Figure 5-1. In the Brink and Contant inertial impaction treatment, the abscissa values were the product of the liquid/gas ratio and the dimensionless inertial parameter, $(\Psi)^{1/2}$, and this grouping has been retained in Figure 5-1. The fact that a straight line log-log relation is obtained for these data is not only an indication of the invalidity of the theoretical semi-log penetration function, it also indicates that the use of the inertial parameter may satisfactorily account for the effect of the secondary variables of particle and drop diameter and gas velocity. Thus, there is reason to believe that a modified inertial impaction theoretical treatment, coupled with a turbulent-mixing capture mechanism, may eventually supply the appropriate theoretical base for correct scrubber performance description. However, from an engineering point of view, Equation (5-1) is entirely adequate for most application or correlation purposes for particulate removal by wet scrubbers, given a preliminary evaluation of the performance constant, K, with the proper dust system.

VI. RESEARCH RECOMMENDATIONS

The correlations developed in this investigation, as well as the successful differentiation of the primary scrubber variables, provide an excellent base for the systematic clarification of dispersed-drop wet scrubber capabilities and limitations for particulate/hydrocarbon removal from combustion process off-gases. It is recommended that additional work be pursued on the following three separate levels, preferably concurrently, and within an integrated overall program:

1. Continuation of literature data correlation.
2. Development of a data-consistent theoretical model.
3. Direct and relevant experimental testing.

A. CONTINUATION OF LITERATURE DATA CORRELATION

This study made use largely of "primary" wet scrubber literature data obtained by the direct experimental testing of equipment in the laboratory or pilot plant. The only industrial data utilized was that of Ingels (1960) on asphalt plants. However, there are many secondary reports of scrubbing data and test results on full-scale plant equipment in the trade journals, but because of time and budget limitations, it was not possible to cover such a secondary material. The first priority in any continuation of this work should be the evaluation of these data in the context of the correlating techniques already developed.

B. DEVELOPMENT OF A SATISFACTORY THEORETICAL MODEL

The failure of the widely-accepted inertial impaction theory to give even a qualitative fit of the prime-variable data for dispersed-liquid wet scrubbers forces the conclusion that this theory is an "emperor's clothes" situation. This theory does not cover the efficiency/scrubber-variable relationships in its present form, and its apparent successes in describing data do not bear close inspection. While a turbulent-agglomeration mechanism serves to provide a rational basis for a gross qualitative interpretation of scrubber performance dependency on operating variables, there are no quantitative predictive theoretical forms to go along with this mechanism. Whether a suitable turbulent agglomeration theory, modified impaction theory or a hybrid model is to be emphasized is not clear at this point, but any theory must (at minimum) explain the following points:

(a) The fundamental anomaly that, for a given dust, penetration is inversely proportional to the feed dust mass concentration.

(b) Inverse proportionality of penetration to liquid-gas ratio and a power of pressure drop.

(c) Effect of dust and water particle size and distribution on penetration.

C. EXPERIMENTAL PROGRAM

One of the major advantages of the correlation in this study is that it describes the conditions necessary for valid comparative rating of scrubber performance, and allows a simple statement of the relative efficiency in the form of the performance constant, K. While the influence of the type of dust on performance constant remains to be examined, the correlation allows testing under non-constant conditions for a given dust without compromising the results. A definitive laboratory experimental program is recommended, utilizing two or three test scrubbers, and covering the following sub-programs:

(a) Confirmation of the proposed performance equations by full-range testing of the prime variables of dust loading, liquid-gas ratio, and scrubber gas velocity (or pressure drop).

(b) Direct verification of the indicated influence of feed pre-agglomeration on the feed dust loading/penetration relationships.

(c) Evaluation of the performance constant, K, for the test scrubbers in terms of nature and mean size of dust.

(d) Separation of the effects of liquid-dust agglomeration from removal processes by (1) independent control of the secondary centrifugal removal force through spin-out diameter variation, and (2) varying inlet particle number and mass concentration independently and measuring the effect on penetration.

(e) Separation of the liquid shearing phenomenon by pre-atomization of the liquid prior to injection into the scrubber.

(f) Evaluation of the nature of condensation-augmentation on scrubbing by pre-formed fog injection in the absence of condensation.

NOMENCLATURE

A, B = Constants

C_d = Dust concentration/unit gas volume, commonly gr/CF

C_f = Drag coefficient, dimensionless

D = Particle diameter

D_c = Count median diameter

D_d = Diameter of Water Droplet

D_g = Mass median diameter

D_o = Mean Sauter drop size, microns

D_p = Diameter of dust particle

E_o = Stage efficiency, constant

E = Overall scrubber efficiency, fractional

E_t = Target efficiency, dimensionless

F = Penetration, weight percent

F_o = Penetration of a single stage

g = Gravitational, constant

K = Proportionality constant

L/G = Ratio of volume flow of liquid to flow of gas at vena contracta

M = Mass concentration

N = Water drop population concentration

N_d = Number concentration of drops, cm^{-3}

N_p = Number concentration of particles, cm^{-3}

n = Number of stages

P = Pressure

V_g = Velocity of gas

V_d = Velocity of water drop

$\overline{V}_g$ = Relative air-water drop velocity, ft/sec $(V_g - V_d)$

W/G = Water/gas volumetric ratio, commonly gal/MCF

X_c = Agglomeration index, $(C_d)(W/G)$

α = Mass loss constant

β = Surface loss constant

μ = Viscosity of gas

μ_L = Liquid viscosity, poises

ρ_L = Liquid drop density

ρ_p = Density of dust particle

σ_g = Geometric mean deviation

σ_L = Liquid surface tension, dynes/cm

Ψ = Separation number, or inertial impaction parameter, dimensionless

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APPENDIX G

QUESTIONNAIRE SURVEY ANALYSIS

QUESTIONNAIRE SURVEY ANALYSIS

Discussion

To complement the survey of the open literature and related government contract reports, two questionnaire surveys were conducted; one covering selected state and municipal or regional control agencies and another covering selected trade or industry associations.

In order to improve the chances of a reasonable return from these surveys, the questionnaires were kept to a fairly simple format, primarily intended to ascertain if pertinent information had been developed in specific areas, such as emission inventories, specific control procedures, legislation in effect, cost of control and solid waste combustion data. Copies of the two questionnaires and the distribution lists for each are appended.

The control agency questionnaire was sent to 45 state and 33 municipal or regional agencies. The response and type of data received as a result of the questionnaire and follow-up contact are summarized in Table G-1.

Certain of the questions asked for specific data, such as types or descriptions of problem pollutants, costs of applied controls, and amounts of waste disposed of by combustion. Responses to some of these questions are given in Tables G-2 through G-4.

A number of control agencies indicated the availability of partial or incomplete unpublished emission inventory data if a personal visit were made to collect the information. The questionable fruitfulness of such data deterred us from pursuing personal visitation of this type. This decision was based on:

(1) an assessment of published inventories which indicated that most of the data were based on estimates rather than detailed surveys; and

(2) phone and letter follow-up which generally confirmed the lack of specific survey data.

The survey of trade and industry associations was less fruitful than the control agency survey. Of the thirty-eight associations contacted, only three provided any hard data. Fifteen others responded, generally to indicate a lack of information.

Table G-1 - Control Agency Survey Summary

Information, Type and Response	State Agencies 45 surveyed, 33 responding		Regional Agencies 33 surveyed, 11 responding		Comments
	No. of Agencies	% of Responding	No. of Agencies	% of Responding	
1. Questionnaire partially completed	30	91	8	73	No questionnaires were totally completed
2. Emission Inventory Data					Only 1 state and 3 regions provided inventories based on actual survey data. Others range from guesstimates to limited source surveys.
a. Partial estimates provided	3	9	3	27	
b. Detailed breakdown provided	2	6	4	36	
c. No data	25	76	1	9	
3. Legislative Data (Controls or standards in effect)					4 regions and 11 states have control legislations. Others have air quality standards only.
a. Some data provided	18	55	7	64	
b. No legislation in effect	11	33	1	9	
c. No data	1	3	-	-	
4. Control Cost Data					Total estimates, ranging from wild guesses to apparently valid approximations.
a. Estimate provided	4	12	4	36	
b. No data	26	79	4	36	
5. Waste Combustion Data					
a. Open burning					One state and two regions ban all open burning, except by variance. Wide variations in quantities burned, dependent on estimating procedures.
i. Total Estimate	5	15	1	9	
ii. Detailed breakdown	4	12	5	45	
iii. Legislative ban	1	3	2	18	
iv. No data	20	61	1	9	
b. Incineration					Many states have little or no municipal incineration. Quantities estimated vary widely.
i. Total estimate	3	9	2	18	
ii. Detailed breakdown	6	18	5	45	
iii. No data	21	64	1	9	
c. Agricultural and special waste burnings					Two regions and two states gave fairly detailed breakdown of agricultural and forestry burning.
i. Partial estimates	6	18	5	45	
ii. No data	24	73	3	27	

Table G-2 - Specific Problem Pollutants Mentioned in Control Agency Response to Question 16

Agency	Pollutants or Sources
California	Photochemically reactive hydrocarbon
Connecticut	Odorants - industrial
Idaho	Open burning of wastes, Tepee burners automobile burning
Illinois	Asphalt oil mists, Mercaptans, Phenols
Kentucky	Mercaptans
Maine	Mercaptans, Rendering plants
Maryland	Drying ovens - can and bottle cap manufacture, Gasoline, Solvent recovery plant odors
Oregon	Organo-sulfur compounds from pulp mills, Rendering plant odors
South Carolina	Mercaptans, Organo-phosphate odors
Cincinnati	Solvents, Gasoline
Philadelphia	Amines, Mercaptans, Acrylics, Phthalic anhydride
Puget Sound	Mercaptans - pulp mills, Amines - rendering plants, Hydrocarbons - asphalt, Terpenes - plywood driers, Resin manufacturing, Re-refining or destruction of wastes
San Francisco Bay Area	Photochemically reactive organics, Carbonyls from incineration

Table G-3 - Control Costs Mentioned in Control Agency Response to Questions 19 and 20

Agency	Question 19- Dollar Cost of Applied Controls	Question 20- Dollar Cost of Control for Total Compliance
Mississippi	3-1/2¢/person	--
Oregon	$6,000,000	$40,000,000
South Carolina	$ 400,000	$22,000,000
Cincinnati	$ 500,000	$ 500,000
Denver	--	$25,000,000
Puget Sound	$8,000,000	$20,000,000
San Francisco Bay Area	$200,000,000	$400,000,000

Table G-4 - Waste Combustion Data Provided by Control Agencies in Response to Question 28

Control Agency	Open Burning					Incineration					Miscellaneous			
	Municipal	Commercial	Industrial	Household	Units or Comments	Municipal	Commercial	Industrial	Household	Units				
Arizona	96.2				ton/day	2.9				ton/day	398 slash fires	9.2 Agriculture	-	ton/day
Connecticut	none				banned	4,057,000	-	-	none	ton/yr	900 Agriculture	445 Demolition & Construction	270 Bulky Wastes	ton/yr
Delaware	none	none	none	10,000	ton/yr	none	20,000	50,000	none	ton/yr	none			
Georgia	-	163,000	18,200	444,600	ton/yr	437,194	-	-	-	ton/yr	-	-	-	-
Idaho	1,688	-	-	-	ton/day	-	-	-	-	-	-	-	-	-
New York (state)	210,000	32,000	21,000	789,000	ton/yr	1,671,000	119,000	119,000	477,000	ton/yr	-	-	-	-
Oregon	25,000				ton/yr	-	-	33,000 Wood Wastes	-	ton/yr	29,000 Forest Slash	17,000 Field Burning	-	ton/yr
Pennsylvania	3,000,000		1,700,000	Included with Mun. & Comm.	ton/yr	1,000,000		300,000	Included with Mun. & Comm.	ton/yr	500,000 Agriculture	-	-	ton/yr
Rhode Island	142,416	-	-	-	ton/yr	135,180		233,611		ton/yr	-	-	-	-
Wisconsin	75,000	-	-	10,000	ton/yr	1,000,000	10,000	1,000	-	ton/yr	-	-	-	-
Denver	none				banned	none	4,378		none	ton/yr	none			
Philadelphia	none				banned	604,000	270,000	-	330,000	ton/yr	-	-	-	-
Puget Sound	28,200	155,000	78,000	9,500	ton/yr	none	46,180	29,900	3,500	ton/yr	406,300	23,800	20,000	ton/yr
San Francisco Bay	none	none	none	2,200	ton/day Banned after 1969	none	400	100	none	ton/day	560 Agriculture	-	-	ton/day

MSA RESEARCH CORPORATION

OMB Clearance Number
85-F-70041
Expires 7-31-71

HYDROCARBON POLLUTANT SURVEY*
POLLUTION CONTROL AGENCY REPORT

For the purposes of this study, the terms "hydrocarbon" and "organic" are synonymous and include all organic compounds or classes of compounds from stationary sources. If for some reason a particular question cannot be answered, write NOT AVAILABLE in the appropriate space. Additional entries, information or comments may be entered in Item No. 29 or on attached sheet. If unpublished information is made available, results will be held CONFIDENTIAL.

Identification No. ☐ For MSAR Use Only

1. Agency
2. Address
3. Date
4. Name of Person Completing Form
5. Title
6. Address & Phone No.

7. Primary Activity in Pollution Control ☐ Air ☐ Water ☐ Solid Waste

8. Jurisdiction (State, County, etc. served by Agency)

Name of Jurisdictional Unit or Subdivision	Area (sq mi)	Population (thousands)	Zoning or Use as % of Total Area				
			Res.	Comm.	Ind.	Agr.	Other

9. If sources other than person designated in Item 4 are utilized in completing this form, indicate below the source and applicable item numbers.

Name	Title	Organization	Item No.

10. Has your agency conducted any surveys of hydrocarbon emissions from stationary sources? ☐ Yes ☐ No ☐ Completed ☐ In Progress

11. Emission surveys completed

Type	Effective Date	Published	Unpublished
Total organic emissions			
Total organic emissions by area subdivision			

---

*Sponsored by Environmental Protection Agency, Air Pollution Control Office, Contract Number EHSD 71-12.

Identification No. ☐ Page 2 of 4

11. Emission surveys completed (continued)

Type	Effective Date	Published	Unpublished
Total organic emissions by industry or operational source			
Specific compounds or classes of emissions (describe)			

If survey results are unpublished, check here ☐ if results could be made available for study. (Confidentiality of unpublished information is assured.)

12. Emission survey in progress

Type	Estimated Completion Date

Check here ☐ if partially completed results could be made available for study.

13. Has your agency compiled tables of hydrocarbon emissions for particular industry or operational sources? ☐ Yes ☐ No

14. Emission tables compiled

Description	Published	Unpublished

If unpublished, check here ☐ if results could be made available for study.

15. Are there specific organic air pollutants that you have identified as being particularly troublesome? ☐ Yes ☐ No
If yes, describe in Item 16.

16. Specific problem pollutants

	Reason for Problem			
Type	Adverse Health Effects	Smog Contribution	Lack of Controls	Other

Identification No. ☐

17. Has legislation been enacted to limit or control organic emissions in your jurisdictional area? ☐ Yes ☐ No
If yes, describe briefly.

Legislation	Legislative Code No.	Time Limit for Compliance

18. Estimate extent to which controls or limits have been applied (percentage estimate for each category or legislation).

Legislative control	Percent

19. Estimate dollar cost of currently applied controls. $__________

20. Estimate dollar cost of control for total compliance. $__________

21. Does your agency have the responsibility for recommending control or abatement procedures for specific emissions? ☐ Yes ☐ No
If yes, have you developed a manual or handbook of control engineering procedures? ☐ Yes ☐ No
If possible, please forward copy of handbook.

22. Has your agency developed any economic evaluations (capital and operating costs) of specific control procedures for organic emissions?
☐ Yes ☐ No
If yes, describe briefly in Item 23.

23.

24. Has your agency developed air quality standards for any organic pollutants? ☐ Yes ☐ No
If yes, describe briefly in Item 25.

25. Air quality standards

Compound or class	Concentration limits

Identification No. ☐

26. Has your agency developed emission standards (or limits) for specific sources of organic emissions? ☐ Yes ☐ No
If yes, describe briefly in Item 27.

27. Type of emission	Emission limits

28. Estimate tonnage of solid waste disposal by combustion for each of the following categories.

Category	Tonnage
Open Burning	
Municipal dump or landfill	
Commercial and Institutional	
Industrial	
Household	
Incineration	
Municipal	
Commercial and Institutional	
Industrial	
Household	
Other (Agricultural, etc.)	

29. Continuation items

Item no.	Additional information

MSA RESEARCH CORPORATION

OMB Clearance Number
85-S-70043
Expires 5-31-71

HYDROCARBON POLLUTANT SURVEY*
TRADE ASSOCIATION REPORT

For the purpose of this study, the terms "hydrocarbon" and "organic" are synonymous and include all organic compounds or classes of compounds from stationary sources.

Identification No ☐ For MSAR Use Only

1. Association	2. Address	3. Date

4. Name of Person Completing Form	5. Title	6. Address & Phone No.

7. If sources other than person designated in Item 4 are utilized in completing this form, indicate below the source and applicable item numbers.

Name	Title	Organization	Item No.

8. Principal industry(ies) represented by association

Description	SIC No.	No. Companies Represented	% of Total Industry

9. Has your association conducted any industry surveys of organic emissions?
☐ Yes ☐ No ☐ Completed ☐ In Progress

10. Emission surveys completed

Type	Effective Date	Published	Unpublished
Total Industry Emissions			
Emissions by Specific Operational Source			

---

*Sponsored by Environmental Protection Agency, Air Pollution Control Office, Contract No. EHSD 71-12.

Identification No. ☐

10. Emission surveys completed (continued)

Type	Effective Date	Published	Unpublished
Particular Compounds or Classes (Describe)			
Other (Describe)			

If survey results are unpublished, check here ☐ if results could be made available for confidential study.

11. Emission surveys in progress

Type	Estimated Completion Date

Check here ☐ if partially completed survey results could be made available for confidential study.

12. Are there specific organic emissions that you have identified as being known or potential pollutant problems? ☐ Yes ☐ No

If yes, describe briefly

13. Have you developed any manuals or handbooks of air pollution control procedures? ☐ Yes ☐ No

If yes, describe

Description	Published	Unpublished

If unpublished, check here ☐ if data could be made available for confidential study.

Identification No. ☐ Page 3 of 3

14. Have you developed any economic evaluations (capital and operating costs) of specific control procedures? ☐ Yes ☐ No

If yes, describe

Description	Published	Unpublished

If unpublished, check here ☐ if results could be made available for confidential study.

15. Are there particular areas of research and development relating to control of hydrocarbon emissions that you feel should be pursued?

☐ Yes ☐ No

If yes, describe briefly

16. Continuation Items, Additional Information or Comments

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APPENDIX H

BREAKDOWN OF FUEL CONSUMPTION AND ESTIMATED EMISSIONS

AND

REVIEW OF ELEMENTARY COMBUSTION STUDIES

1. Breakdown of Fuel Consumption and Estimated Emissions

In Tables H-1 through H-10 are presented state and regional breakdowns of fuel consumption and estimated hydrocarbon emissions for each of the major fossil fuels. These data amplify the discussion and summary presented in Volume I, Section III.

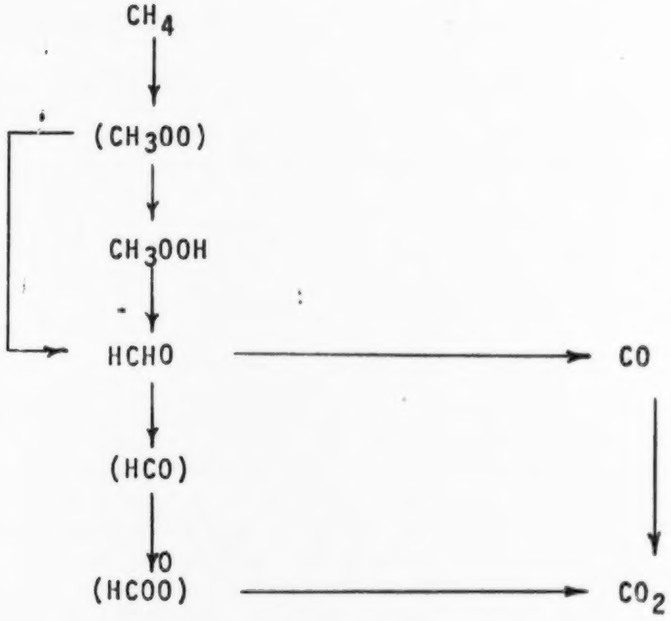
Data sources for the fuel consumption by area and consuming sector were the Federal Power Commission (1968) and the U.S. Bureau of Mines (1968, 1970).

2. Review of Elementary Combustion Studies

In the course of the literature review on hydrocarbon emissions from combustion sources, it was found that very few studies have been made of the trace organic constituents from combustion under field or full-scale conditions. Most of the reported studies have treated only "total gaseous hydrocarbon" measured by flame ionization or, in a few cases, reported determination of chemical groups, such as aldehydes (or total oxygenates), organic acids, unsaturates, and the like. As an attempt to gain some insight into the types and amounts of particular chemical species emitted from combustion sutides reported in the literature were briefly reviewed.

Combustion processes are basically chemical reaction between a fuel and an oxidant at more or less elevated temperatures. A generalization about such reactions is that the reaction complexity increases as the chemical complexity of the reactants increases. Thus, our understanding of the reactions which take place is based primarily on analogies drawn from studies of the simpler systems. No attempt was made to review all of the literature on combustion. For good general reviews, reference may be made to such texts as Lewis and von Elbe (1961) and Lewis, Pease and Taylor (1956).

The oxidation of simple hydrocarbons is generally viewed as a free radical initiated, chain branching mechanism, with the critical intermediates being partially oxygenated species containing peroxy, hydroperoxy, and aldehyde linkages. Newman and Gål (1968) have summarized the sequence of elementary steps in the oxidation of methane by the following scheme:



Although the concentrations and total number of stable intermediates and final combustion products vary with the conditions of the particular study, the consensus of investigators of elementary combustion studies is that the most common species formed are formaldehyde, acetaldehyde, formic acid, acrolein and acetone. Reference may be made to Bonner and Tipper (1965) and Pease (1934, 1935) as typical studies leading to this conclusion.

Actual combustion processes are complicated by the fact that most fuels (and their combustion intermediates) can undergo thermal degradation, cracking or condensation reactions which do not evolve direct oxication. Thus, studies of thermal decomposition in the absence or insufficiency of oxygen must be included in our consideration of potential contaminant emissions. Examples of such studies are the work of Holmes and Shaw (1961), Roberts and Clough (1963), and Martin (1965), on the thermal decomposition of cellulosic materials. Again, the stable intermediates identified were the lower aldehydes, ketones, and acids. In addition to the oxygenated species, the low molecular weight hydrocarbons, principally methane, ethane and ethylene, have been identified as stable products.

Most of the fundamental studies of combustion have, in order to allow menaingful experimental design and interpretation, been limited to simple hydrocarbon fuels. When one considers the potential variety of combustible material that is involved in the combustion of fuels and wastes, the extrapolation of the results of fundamental studies becomes quite tenuous. The breakdown of types and concentrations of emission products from combustion thus depends on specific studies of the particular fuel or waste composition and the combustion process used. Such specific studies have not been made, except for limited special cases, such as current studies of combustion of high plastic content wastes.

Table H-1 - State Breakdown of Coal Consumption by Electric Utilities (1968)

			Emissions (tons)	
Rank	State	Coal Consumed (10^3 tons)	Hydrocarbon (as CH_4)	Aldehydes
1	Ohio	29,569	4,435	74
2	Illinois	27,123	3,918	68
3	Pennsylvania	25,160	3,774	63
4	Indiana	21,745	3,263	54
5	Michigan	18,983	2,847	47
6	North Carolina	15,056	2,259	38
7	Alabama	14,368	2,156	36
8	Kentucky	13,255	1,989	33
9	New York	13,152	1,973	33
10	West Virginia	13,021	1,953	33
11	Tennessee	12,835	1,926	32
12	Virginia	7,869	1,181	20
13	Wisconsin	7,626	1,145	19
14	Maryland	7,447	1,118	19
15	Missouri	7,421	1,113	19
16	Georgia	7,118	1,068	18
17	New Jersey	5,025	755	13
18	Florida	4,481	672	11
19	Minnesota	4,205	632	11
20	Iowa	2,803	420	7
21	Colorado	2,742	411	7
22	North Dakota	2,732	410	7
23	Massachusetts	2,730	410	7
24	Arizona	2,722	410	7
25	Connecticut	2,585	389	6
26	Wyoming	2,085	314	5
27	South Carolina	1,822	273	5
28	Delaware	1,368	206	3
29	New Hampshire	765	116	2
30	District of Columbia	725	110	2
31	Nevada	536	81	1
32	Kansas	461	69	1
33	Nebraska	419	63	1
34	Utah	396	60	1
35	Mississippi	241	36	1
36	Rhode Island	110	17	-
37	Vermont	32	5	-
	Totals	280,733	41,977	704

Table H-2 - Regional And State Breakdown of Non-Utility Consumption of Coal, 1968(a)

Region & State	Industrial(b)			Domestic & Commercial		
	Coal Consumed 10^3 tons	Emissions (ton/yr) Hydrocarbons	Aldehydes	Coal Consumed 10^3 tons	Emissions (ton/yr) Hydrocarbons	Aldehydes
New England						
Massachusetts	337	169	0.8	114	171	0.3
Connecticut	346	173	0.9	1	--	--
Me., N.H., Vt., & R.I.	141	71	0.4	22	33	--
Middle Atlantic						
New York	6,728	3,364	16.8	153	230	0.4
New Jersey	878	439	2.2	7	11	--
Pennsylvania	9,247	4,624	23.1	699	1,049	1.8
E. North Central						
Ohio	14,949	7,475	37.4	2,033	3,050	5.1
Indiana	6,203	3,102	15.5	998	1,497	2.5
Illinois	8,863	4,432	22.2	3,312	4,968	8.3
Michigan	9,567	4,784	23.9	1,474	2,211	3.7
Wisconsin	4,418	2,209	11.0	1,995	2,993	5.0
W. North Central						
Minnesota	1,123	562	2.8	795	1,193	1.3
Iowa	1,788	894	4.5	263	395	0.7
Missouri	1,932	966	4.8	149	224	0.4
North & South Dakota	341	171	0.9	312	468	0.8
Nebraska & Kansas	214	107	0.5	51	77	0.1
South Atlantic						
Delaware & Maryland	1,046	523	2.6	90	135	0.2
District of Columbia	131	66	0.3	83	125	0.2
Virginia	4,740	2,370	11.9	720	1,080	1.8
West Virginia	5,505	2,753	13.8	425	638	1.1
North Carolina	2,335	1,168	5.8	619	929	1.6
South Carolina	1,159	580	2.9	275	413	0.7
Georgia & Florida	573	287	1.4	205	308	0.5
East S. Central						
Kentucky	2,326	1,163	5.8	660	840	1.4
Tennessee	2,852	1,426	7.1	584	876	1.5
Alabama & Mississippi	1,896	948	4.7	105	158	0.3
West S. Central						
Ark., La., Okla., & Texas	115	58	0.3	13	20	--
Mountain						
Colorado	501	251	1.3	316	474	0.8
Utah	338	169	0.8	134	201	0.3
Montana & Idaho	216	108	0.5	351	527	0.9
Wyoming	234	117	0.6	30	45	0.1
New Mexico	16	8	--	4	6	--
Arizona & Nevada	16	8	--	18	27	--
Pacific						
Washington & Oregon	306	153	0.8	143	215	0.4
California	14	7	--	11	17	--
Alaska	635	318	1.6	37	56	0.1
Totals	92,029	46,023	229.9	17,101	25,670	42.3

(a) Bureau of Mines data

(b) excludes coke and gas plants

Table H-3 - State Breakdown of Natural Gas Consumption by Electric Utilities (1968)

Rank	State	Gas Consumed (10^6 cu ft)	Emissions, (tons) Total Hydrocarbons	Emissions, (tons) Aldehydes
1	Texas	731,359	1,462	1,098
2	California	674,713	1,349	1,011
3	Louisiana	290,920	582	435
4	Oklahoma	147,642	295	222
5	Florida	127,881	256	192
6	Kansas	120,805	242	180
7	New York	97,849	196	147
8	Mississippi	76,496	153	114
9	Arkansas	72,142	144	108
10	Illinois	61,751	124	93
11	Iowa	54,810	110	81
12	Minnesota	44,599	89	66
13	Arizona	41,171	82	63
14	Nebraska	29,343	59	45
15	Colorado	27,466	55	42
16	South Carolina	27,142	54	42
17	New Mexico	23,965	48	36
18	Missouri	23,330	47	36
19	Tennessee	22,034	44	33
20	New Jersey	18,263	37	27
21	Wisconsin	17,883	36	27
22	Georgia	14,944	30	21
23	Nevada	14,740	30	21
24	Alabama	11,467	23	18
25	Ohio	6,629	13	9
26	Indiana	5,635	11	9
27	Utah	4,224	8	6
28	Massachusetts	3,477	7	6
29	Pennsylvania	3,048	6	6
30	South Dakota	1,670	3	3
	Totals	2,797,398	5,595	4,197

TABLE H-4 - REGIONAL AND STATE BREAKDOWN OF NATURAL GAS CONSUMPTION IN 1968[a] INDUSTRIAL USAGE[b]

Region & State	Gas Consumption MMcf	Emissions (tons/yr) Hydrocarbons	Aldehydes
New England			
Connecticut	15,045	53	23
Me, N.H., Vt.	1,387	5	2
Massachusetts	22,379	78	34
Rhode Island	5,188	18	8
Middle Atlantic			
New Jersey	70,850	248	106
New York	91,679	321	138
Pennsylvania	314,913	1,102	472
East North Central			
Illinois	336,393	1,177	505
Indiana	231,137	809	346
Michigan	250,906	879	376
Ohio	350,281	1,226	525
Wisconsin	117,315	411	176
West North Central			
Iowa	82,646	289	124
Kansas	147,183	515	221
Minnesota	88,518	310	133
Missouri	94,287	330	141
Nebraska	48,166	169	72
North Dakota	2,612	9	4
South Dakota	4,101	14	6
South Atlantic			
Delaware	11,377	40	17
Florida	88,299	309	132
Georgia	140,115	490	210
Maryland and D. C.	37,514	131	56
North Carolina	60,538	212	91
South Carolina	68,641	240	103
Virginia	42,493	149	64
West Virginia	88,069	308	132
East South Central			
Alabama	171,755	601	258
Kentucky	51,969	182	78
Mississippi	119,590	419	179
Tennessee	107,476	376	161
West South Central			
Arkansas	138,997	487	209
Louisiana	864,848	3,027	1,297
Oklahoma	118,948	416	178
Texas	1,696,231	5,937	2,544
Mountain			
Arizona	54,613	191	82
Colorado	83,683	293	126
Idaho	24,637	86	37
Montana	23,155	81	35
Nevada	8,693	30	13
New Mexico	76,864	269	115
Utah	53,639	188	80
Wyoming	34,794	122	52
Pacific			
Alaska	2,677	9	4
California	544,292	1,905	816
Oregon	51,755	181	78
Washington	93,370	327	140
Totals	7,134,018	24,969	10,699

(a) Bureau of Mines data

(b) excludes utilities, but includes refinery fuel use

Table H-5 - Regional and State Breakdown of Natural Gas Consumption in 1968(a), Residential and Commercial and Institutional Usage

	Residential			Commercial and Institutional		
	Gas Consumed	Emissions (tons/yr)		Gas Consumed	Emissions (tons/yr)	
Region & State	MMcf	Hydrocarbons	Aldehydes	MMcf	Hydrocarbons	Aldehydes
New England						
Connecticut	26,437	13	133	11,224	6	56
Me., N.H., Vt.	3,571	2	18	1,672	1	9
Massachusetts	74,919	38	375	25,396	13	128
Rhode Island	10,605	5	53	3,411	2	18
Middle Atlantic						
New Jersey	137,116	69	685	32,546	16	163
New York	319,282	160	1,596	122,885	62	615
Pennsylvania	285,978	143	1,430	87,620	44	438
E. North Central						
Illinois	392,325	196	1,961	174,565	87	873
Indiana	145,955	73	730	60,661	30	304
Michigan	315,694	158	1,579	117,124	59	585
Ohio	444,964	223	2,225	165,414	83	828
Wisconsin	93,425	47	466	36,067	18	180
W. North Central						
Iowa	84,936	43	425	48,034	24	240
Kansas	89,372	45	446	46,232	23	231
Minnesota	90,410	45	453	65,536	33	328
Missouri	138,764	69	694	79,821	40	399
Nebraska	53,376	27	268	41,765	21	209
North Dakota	7,169	4	36	7,072	4	35
South Dakota	10,302	5	51	10,723	5	54
South Atlantic						
Deleware	7,068	4	35	2,084	1	10
Florida	11,318	6	56	21,890	11	110
Georgia	84,072	42	420	36,034	18	180
Maryland & D.C.	79,015	40	395	30,419	15	153
North Carolina	24,646	12	124	20,624	10	103
South Carolina	16,756	8	84	10,544	5	53
Virginia	43,582	22	218	24,594	12	123
West Virginia	54,665	27	274	20,402	10	103
E. South Central						
Alabama	51,708	26	259	34,749	17	174
Kentucky	75,824	38	379	36,089	18	180
Mississippi	29,526	15	148	18,297	9	91
Tennessee	43,784	22	219	38,325	19	191
W. South Central						
Arkansas	56,346	28	283	37,886	19	190
Louisiana	77,762	39	389	56,937	29	285
Oklahoma	74,782	37	374	42,751	21	214
Texas	211,763	106	1,058	139,442	70	698
Mountain						
Arizona	26,681	13	134	23,389	12	118
Colorado	78,371	39	391	47,287	24	236
Idaho	6,545	3	33	6,374	3	31
Montana	19,711	10	98	13,651	7	69
Nevada	5,493	3	28	6,997	4	35
New Mexico	31,568	16	158	30,713	15	154
Utah	40,779	20	204	8,114	4	40
Wyoming	12,592	6	63	11,637	6	59
Pacific						
Alaska	2,293	1	11	4,713	2	24
California	517,636	259	2,588	189,903	95	950
Oregon	15,126	8	76	7,874	4	39
Washington	26,342	13	131	16,244	8	81
Totals	4,450,354	2,229	22,254	2,075,736	1,035	10,387

Table H-6 - Consumption and Emissionf From Fuel Oil Usage by Electric Utilities

P.A.D. District and State	Electric utility company use (Thousand barrels)				1969 Emissions (Tons/year)	
	Distillate-type oils		Residual-type oils(1)			
	1969	1968(2)	1969	1968	Total Hydrocarbon	Aldehyde
District 1:						
Connecticut	331	28	18,215	12,772	1,947	389
Delaware	85	56	1,086	454	123	25
District of Columbia	--	--	3,236	1,432	340	68
Florida	290	314	35,686	32,261	3,759	752
Georgia	180	176	493	406	71	14
Maine	96	115	4,727	4,986	506	101
Maryland	408	238	4,143	1,440	478	96
Massachusetts	370	217	31,490	23,450	3,345	669
New Hampshire	3	3	2,092	1,305	220	44
New Jersey	565	430	34,028	26,643	3,632	726
New York	561	475	43,565	34,971	4,633	927
North Carolina	828	447	693	174	160	32
Pennsylvania	2,073	1,399	20,557	10,527	2,376	475
Rhode Island	17	36	3,152	2,426	333	67
South Carolina	490	205	1,582	680	218	44
Vermont	108	19	130	169	25	5
Virginia	486	99	9,350	362	1,033	207
West Virginia	29	22	196	131	24	5
Total	6,920	4,279	214,421	155,089	23,223	4,646
District 2:						
Illinois	494	183	1,171	515	175	35
Indiana	195	165	271	223	49	10
Iowa	258	229	60	69	33	7
Kansas	171	168	188	264	38	8
Kentucky	135	119	35	12	18	4
Michigan	320	269	1,147	920	154	31
Minnesota	416	262	752	568	123	25
Missouri	123	122	76	57	21	4
Nebraska	107	86	78	46	19	4
North Dakota	80	66	11	18	10	2
Ohio	467	450	397	328	91	18
Oklahoma	42	38	6	24	5	1
South Dakota	64	54	78	25	15	3
Tennessee	3	3	--	--	--	--
Wisconsin	237	34	175	187	43	9
Total	3,112	2,248	4,445	3,256	794	161
District 3:						
Alabama	142	138	5	--	15	3
Arkansas	12	9	318	149	35	7
Louisiana	79	44	13	21	10	2
Mississippi	1	1	289	100	30	6
New Mexico	9	9	33	26	4	1
Texas	1,487	1,445	46	34	161	32
Total	1,730	1,646	704	330	255	51
District 4:						
Colorado	19	21	233	103	26	5
Idaho	15	7	--	--	2	--
Montana	14	7	105	23	12	2
Utah	25	21	1,619	1,432	173	35
Wyoming	18	16	9	21	3	--
Total	91	72	1,966	1,579	216	42
District 5:						
Alaska	207	177	195	162	42	8
Arizona	6	7	40	43	5	1
California	29	28	19,761	18,978	2,078	416
Hawaii	52	38	6,029	5,439	639	128
Nevada	11	14	51	58	7	1
Oregon	--	--	8	10	1	--
Washington	--	--	14	12	1	--
Total	305	264	26,098	24,702	2,773	554
United States, total	12,158	8,509	247,634	184,956	27,261	5,454

(1) Source: Federal Power Commission
(2) Revised to include data for gas-turbine plants

Table H-7 - Consumption and Emissions from Industrial (Excluding Oil Companies) Usage of Fuel Oil

P.A.D. District and State	Industrial Use (Thousand barrels)				1969 Emissions (Tons/year)	
	Distillate fuel oils		Residual fuel oils			
	1969	1968	1969	1968	Total Hydrocarbon	Aldehyde
District 1:						
Connecticut	513	905	9,411	10,941	625	219
Delaware	146	153	3,087	2,602	204	71
District of Columbia	4	5	104	63	7	2
Florida	1,041	1,057	5,424	4,905	407	158
Georgia	929	1,005	5,743	6,184	420	160
Maine	371	373	1,999	1,261	149	58
Maryland	743	833	2,225	2,323	187	78
Massachusetts	833	957	10,316	10,764	703	252
New Hampshire	63	115	1,203	594	80	28
New Jersey	1,935	1,904	13,304	14,009	960	361
New York	3,125	4,086	16,055	18,496	1,208	468
North Carolina	818	1,059	3,563	2,910	276	109
Pennsylvania	2,489	3,226	9,981	12,730	786	314
Rhode Island	245	238	1,953	1,722	138	51
South Carolina	405	398	1,104	1,477	95	40
Vermont	116	197	395	235	32	13
Virginia	939	997	1,178	1,590	133	64
West Virginia	370	433	1,516	1,561	119	47
Total	15,090	17,941	88,561	94,369	6,529	2,489
District 2:						
Illinois	1,838	2,115	5,139	6,179	440	185
Indiana	1,169	1,206	2,503	4,620	231	102
Iowa	245	257	42	51	18	11
Kansas	110	120	419	354	33	13
Kentucky	660	605	707	599	86	43
Michigan	1,706	2,044	2,804	2,307	284	130
Minnesota	910	1,015	2,428	2,144	210	89
Missouri	532	559	1,223	518	111	48
Nebraska	47	67	249	130	19	7
North Dakota	145	100	57	19	13	7
Ohio	2,937	2,936	3,434	3,339	401	195
Oklahoma	143	207	349	334	31	13
South Dakota	89	72	33	26	8	4
Tennessee	584	676	758	276	85	40
Wisconsin	685	714	807	1,005	94	46
Total	11,800	12,693	20,952	21,901	2,064	933
District 3:						
Alabama	826	790	1,483	817	145	66
Arkansas	212	194	136	455	22	12
Louisiana	797	773	994	433	113	54
Mississippi	528	466	62	106	37	23
New Mexico	249	210	4	7	16	11
Texas	1,543	1,248	452	710	126	74
Total	4,155	3,681	3,131	2,578	459	240
District 4:						
Colorado	226	763	1,075	748	82	32
Idaho	518	621	166	114	43	25
Montana	148	114	232	102	24	11
Utah	436	493	3,127	3,081	224	84
Wyoming	317	201	338	235	41	20
Total	1,645	2,192	4,938	4,280	414	172
District 5:						
Alaska	384	375	681	571	67	30
Arizona	1,476	1,345	70	16	97	63
California	5,116	4,766	7,710	7,690	808	377
Hawaii	228	162	524	515	47	21
Nevada	324	305	2	--	20	14
Oregon	1,122	1,047	1,778	1,436	183	84
Washington	1,116	1,288	2,307	2,308	216	95
Total	9,766	9,288	13,072	12,536	1,438	684
United States, total	42,456	45,795	130,654	135,664	10,904	4,518

Table H-8 - Consumption and Emissions from Oil Company Usage of Fuel Oil

	Oil Company Use (Thousand barrels)				1969 Emissions (Tons/year)	
	Distillate type oils		Residual type oils(1)			
P.A.D. District and State	1969	1968	1969	1968	Total Hydrocarbon	Aldehydes
District 1:						
Connecticut	269	48	77	80	22	13
Delaware	57	6	122	125	11	5
District of Columbia	10	1	5	4	1	--
Florida	349	152	247	205	38	20
Georgia	66	17	3	16	4	3
Maine	49	7	14	17	4	2
Maryland	281	45	392	462	42	20
Massachusetts	104	42	79	203	12	6
New Hampshire	1	2	3	3	--	--
New Jersey	221	64	6,344	6,681	414	143
New York	120	73	67	68	12	6
North Carolina	86	82	46	43	8	5
Pennsylvania	1,761	1,408	4,743	5,524	410	174
Rhode Island	62	13	11	13	5	3
South Carolina	72	34	102	100	12	5
Vermont	11	2	4	1	1	--
Virginia	106	67	185	147	18	8
West Virginia	101	16	16	--	7	5
Total	3,726	2,079	12,460	13,692	1,009	418
District 2:						
Illinois	1,818	823(2)	3,268	2,448	320	145
Indiana	1,877	1,200	3,831	4,101	360	159
Iowa	30	16	--	--	2	1
Kansas	29	16	797	794	52	18
Kentucky	22	33	50	50	4	2
Michigan	274	159	851	818	71	29
Minnesota	29	71	870	887	57	19
Missouri	24	51	469	493	31	11
Nebraska	9	4	--	--	--	--
North Dakota	10	9	372	472	24	8
Ohio	302	95	929	1,161	78	32
Oklahoma	16	15	197	406	13	5
South Dakota	27	18	--	--	2	1
Tennessee	15	34	2	10	1	--
Wisconsin	215	94	64	116	18	10
Total	4,697	2,638(2)	11,700	11,756	1,033	402
District 3:						
Alabama	11	18	41	42	3	1
Arkansas	9	15	27	28	2	1
Louisiana	940	864	21	19	61	40
Mississippi	7	15	131	135	9	3
New Mexico	11	13	3	7	1	--
Texas	2,164	1,898	1,020	1,017	201	112
Total	3,142	2,823	1,243	1,248	277	157
District 4:						
Colorado	128	10	1	4	8	5
Idaho	5	6	1	--	--	--
Montana	60	10	683	681	47	17
Utah	115	83	400	420	32	13
Wyoming	551	522	482	487	65	33
Total	859	631	1,567	1,592	152	68
District 5:						
Alaska	153	150	16	16	11	7
Arizona	17	16	--	--	1	--
California	514	1,004	6,550	8,098	445	129
Hawaii	13	12	666	679	43	15
Nevada	111	108	--	--	7	5
Oregon	214	92	324	305	34	16
Washington	411	422	2,033	1,943	155	60
Total	1,443	1,804	9,589	11,041	696	232
United States, total	13,867	9,975(2)	36,559	39,329	3,167	1,277

(1) Includes a small amount of crude oil
(2) Revised

Table H-9 - Consumption and Emissions from Commercial and Institutional Usage of Fuel Oil*

P.A.D. District and State	Heating Oils (Thousand Barrels)						1969 Emissions (Tons/year)	
	No. 5		No. 6		Total		Total Hydrocarbon	Aldehydes
	1969	1968	1969	1968	1969	1968		
District 1:								
Connecticut	34	227	4,706	3,630	4,740	3,857	299	100
Delaware	195	135	228	181	423	316	27	9
District of Columbia	505	762	7,161	6,841	7,666	7,603	483	161
Florida	100	51	400	745	500	796	32	11
Georgia	1,542	597	806	529	2,348	1,126	148	49
Maine	385	141	1,582	1,177	1,967	1,318	124	41
Maryland	1,301	1,383	3,817	3,134	5,118	4,517	322	107
Massachusetts	7,544	7,498	22,129	24,277	29,673	31,775	1,870	617
New Hampshire	382	120	635	322	1,017	442	64	21
New Jersey	1,170	1,102	11,659	11,912	12,829	13,014	808	267
New York	1,994	2,718	57,533	57,524	59,527	60,242	3,750	1,238
North Carolina	579	552	503	432	1,082	984	68	22
Pennsylvania	4,941	5,635	6,447	6,294	11,388	11,929	717	239
Rhode Island	420	325	1,367	1,204	1,787	1,529	113	38
South Carolina	247	220	58	147	305	367	19	6
~~Vermont~~	18	39	123	81	141	120	9	3
Virginia	430	653	1,304	1,893	1,734	2,546	109	36
West Virginia	170	113	21	47	191	160	12	4
Total	21,957	22,271	120,479	120,370	142,436	142,641	8,974	2,969
District 2:								
Illinois	7,526	6,896	7,138	6,910	14,664	13,806	924	308
Indiana	524	329	1,786	1,355	2,310	1,684	145	48
Iowa	142	154	61	66	203	220	13	4
Kansas	10	33	16	46	26	79	2	1
Kentucky	6	4	97	17	103	21	6	2
Michigan	422	365	833	480	1,255	845	79	26
Minnesota	593	119	421	78	1,014	197	64	31
Missouri	1,004	1,367	640	670	1,644	2,037	104	35
Nebraska	62	84	73	124	135	208	9	3
North Dakota	10	4	10	2	20	6	1	--
Ohio	101	124	328	249	429	373	27	9
Oklahoma	2	--	5	10	7	10	--	--
South Dakota	33	3	26	15	59	18	4	1
Tennessee	10	25	--	--	10	25	1	--
Wisconsin	679	430	324	350	1,003	780	63	21
Total	11,124	9,937	11,758	10,372	22,882	20,309	1,442	489
District 3:								
Alabama	74	74	--	--	74	74	5	2
Arkansas	--	--	--	--	--	--	--	--
Louisiana	--	--	6	--	6	--	--	--
Mississippi	50	--	50	--	100	--	6	2
New Mexico	2	4	--	--	2	4	--	--
Texas	73	65	503	114	576	179	36	12
Total	199	143	559	114	758	257	47	16
District 4:								
Colorado	223	215	223	112	446	327	28	9
Idaho	62	31	103	47	165	78	10	3
Montana	200	284	26	135	226	419	14	5
Utah	389	277	373	288	762	565	48	16
Wyoming	215	100	295	203	510	303	32	11
Total	1,089	907	1,020	785	2,109	1,692	132	44
District 5:								
Alaska	3	--	19	13	22	13	1	--
Arizona	19	19	16	16	35	35	2	1
California	942	938	1,495	1,490	2,437	2,428	154	51
Hawaii	110	101	159	148	269	249	17	6
Nevada	27	30	24	29	51	59	3	1
Oregon	2,060	1,868	1,340	1,135	3,400	3,003	214	71
Washington	2,327	2,292	1,369	1,348	3,696	3,640	233	78
Total	5,488	5,248	4,422	4,179	9.910	9,427	624	208
United States, total	39,057	38,506	138,238	135,820	178,095	174,326	11,219	3,726

*May include some usage as industrial heating

Table H-10 - Consumption and Emissions from Domestic Usage of Fuel Oil*

	Heating Oils (Thousand Barrels) 1969					1969 Emissions (Tons/year)	
	No. 1						
P.A.D. District and State	Automatic Burners	Other Heating	No. 2	No. 4	Total	Total Hydrocarbons	Aldehydes
District 1:							
Connecticut	219	141	16,896	1,525	18,781	1,183	789
Delaware	245	128	2,891	10	3,274	206	137
District of Columbia	74	400	2,090	165	2,729	172	115
Florida	101	560	3,178	78	3,917	247	165
Georgia	89	111	1,919	--	2,119	133	89
Maine	262	636	8,009	208	9,115	574	383
Maryland	238	57	11,775	182	12,252	772	515
Massachusetts	961	337	49,461	2,183	52,942	3,335	2,223
New Hampshire	170	183	6,637	45	7,035	443	295
New Jersey	384	150	40,361	7,828	48,723	3,070	2,047
New York	2,045	684	79,449	10,360	92,538	5,830	3,887
North Carolina	723	568	10,614	51	11,956	753	502
Pennsylvania	800	252	37,932	1,725	40,709	2,565	1,710
Rhode Island	37	105	7,068	100	7,310	461	307
South Carolina	266	266	3,761	100	4,393	277	185
Vermont	154	67	4,644	83	4,948	312	208
Virginia	527	255	10,261	254	11,297	712	475
West Virginia	4	2	593	6	605	38	25
Total 1969	7,299	4,902	297,539	24,903	334,643	21,083	14,057
Total 1968	8,557	5,873	291,759	23,456			
District 2:							
Illinois	2,316	695	19,429	952	23,392	1,474	983
Indiana	1,727	1,022	14,068	250	17,067	1,075	717
Iowa	1,453	487	5,204	16	7,160	451	301
Kansas	106	18	609	11	744	47	31
Kentucky	251	67	1,333	32	1,683	106	71
Michigan	4,943	1,869	19,347	301	26,460	1,667	1,111
Minnesota	2,380	983	10,914	154	14,431	909	606
Missouri	537	438	4,918	222	6,115	385	257
Nebraska	285	107	1,578	--	1,970	124	83
North Dakota	730	133	2,663	14	3,540	223	149
Ohio	1,427	185	13,398	239	15,249	961	641
Oklahoma	99	91	529	--	719	45	30
South Dakota	632	124	1,477	--	2,233	141	94
Tennessee	49	65	1,801	--	1,915	121	81
Wisconsin	2,457	958	15,883	542	19,840	1,250	833
Total 1969	19,392	7,242	113,151	2,733	142,518	8,979	5,988
Total 1968	21,143	8,083	115,617	2,367			
District 3:							
Alabama	18	8	301	--	327	21	14
Arkansas	28	14	346	--	388	24	16
Louisiana	32	19	606	--	657	41	27
Mississippi	26	30	671	--	727	46	31
New Mexico	8	30	187	--	225	14	9
Texas	413	240	1,040	3	1,696	107	71
Total 1969	525	341	3,151	3	4,020	253	168
Total 1968	513	312	1,650	6			
District 4:							
Colorado	355	257	617	--	1,229	77	51
Idaho	876	689	1,708	3	3,276	206	137
Montana	89	564	544	--	1,197	75	50
Utah	92	364	667	32	1,155	73	49
Wyoming	14	37	670	1	722	45	30
Total 1969	1,426	1,911	4,206	36	7,579	476	317
Total 1968	1,797	1,615	5,646	50			
District 5:							
Alaska	848	--	1,660	--	2,508	158	105
Arizona	62	--	115	--	177	11	7
California	293	--	947	--	1,240	78	52
Hawaii	19	--	109	--	128	8	5
Nevada	95	--	376	--	471	30	20
Oregon	1,958	--	4,827	--	6,785	427	285
Washington	3,387	--	8,312	--	11,699	737	491
Total 1969	6,662	--	16,346	--	23,008	1,449	965
Total 1968	6,302	--	15,936	--			
United States total, 1969	35,304	14,396	434,393	27,675	511,768	32,240	21,495
United States total, 1968	38,312	15,883	430,608	25,879			

*May include some commercial usage

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APPENDIX I

WASTE COMBUSTION EMISSION FACTORS
AND
MUNICIPAL WASTE BREAKDOWN

1. Waste Combustion Emission Factors

Introduction

The estimation of hydrocarbon emissions from solid waste combustion detailed in Volume I, Section III, required the application of selected emission factors for the various waste combustion modes. This appendix summarizes the published emission factors utilized in the development of the waste combustion emission estimates.

Discussion

A review of the literature on solid waste combustion emission disclosed a variety of emission factors, ranging from those derived from analytical measurement of the emissions from full scale operations to estimates and extrapolations from limited small scale test data. Many of the reported values are estimates developed by the author of the particular publication from his evaluation of prior literature and, particularly in the case of those reported by Duprey (1968) and McGraw and Duprey (1971), include unpublished data and private communications.

In summarizing the reported values, as shown in Table I-1, the source or type of information used in developing the reported factors are noted under the column headed "Comments".

The selection of average or "typical" emission factors from the wide range of reported values was highly arbitrary. Not only are the analytical measurements supporting the reported values poorly documented, but, in addition, little attempt was made to classify the type or composition of the waste being burned. The wide variety of wastes handled and the extreme ranges of actual combustion conditions makes assignment of 'typical' factors quite speculative.

In selecting the values shown in Table I-2, used for our emission estimates, an attempt was made to give greater weight to those data based on full-scale or reasonably simulated test conditions. Also weighted heavily were those studies which attempted to obtain detailed component breakdowns. Much of the reported emission data is based on measurement of total gaseous hydrocarbons by flame ionization analysis and thus does not generally include the contribution of such species as aldehydes and organic acids. Those few

Table I-1 - Summary of Emission Factors for Waste Combustion

Combustion Mode	Emission Factors, in lbs/ton of waste burned Total Organics	Total Hydrocarbons	Saturated Hydrocarbons	Unsaturated Hydrocarbons	Organic Acids	Aldehydes	PAH	Comments	References
Municipal Incineration (multiple chamber)		1.5						Consensus of literature data	McGraw & Duprey (1971)
		0.3						Consensus of literature data	Duprey (1968)
	0.8		0.15	0.1	0.05	0.3		Review of Bay Area studies	Feldstein, et al (1963)
		1.58 (ave)						Simulated full-scale test measurements	Rose, et al (1959)
		0.3 - 6.5						Simulated full-scale test measurements	Stenburg, et al (1960, 196
		0.9 - 6.3			0.06 - 0.16	0.001-0.84		Full scale test data	A. D. Little (1970)
		2.7					0.005	Consensus of literature and test data	A. D. Little (1970)
Domestic Incineration (single chamber)		2						With primary air -- literature consensus	McGraw & Duprey (1971)
		100						Without primary air -- literature consensus	McGraw & Duprey (1971)
	252							Emission factor used for "residential burning"	Bay Area APCD (1969)
		1 - 2			2 - 7	2.5-5.5		Consensus of literature data	Duprey (1968)
	250		30	36	24	35		Rework of Yocom (1956), "Backyard & Single Chamber"	Feldstein, et al (1963)
		20						Estimated from literature data	Hovey, et al (1966)
Industrial and Commercial Incineration		3						Multiple Chamber -- literature consensus	McGraw & Duprey (1971)
		15						Single chamber -- literature consensus	McGraw & Duprey (1971)
		20						Conical burners -- municipal refuse	McGraw & Duprey (1971)
		11						Conical burners -- wood wastes	McGraw & Duprey (1971)
							0.005 -0.029	Full scale test data	Hangebrauck, et al (1967)
	90							"Single chamber" emission factor	Bay Area APCD (1969)
	0.8							"Double chamber" and "Silo" wood burner	Bay Area APCD (1969)
		0.5-0.8			3	0.2-1		Literature Consensus -- multiple chamber	Duprey (1968)
		2			6-25	2-3		Literature consensus -- flue fed	Duprey (1963)

Table I-1 (continued)

Combustion Mode	Total Organics	Total Hydrocarbons	Saturated Hydrocarbons	Unsaturated Hydrocarbons	Organic Acids	Aldehydes	PAH	Comments	Reference
Open Burning		30						Municipal Refuse -- literature consensus	McGraw & Duprey (1971)
		4-20						Agricultural Refuse -- literature consensus	McGraw & Duprey (1971)
		30						Auto components -- literature consensus	McGraw & Duprey (1971)
		30						Municipal Refuse -- literature consensus	Duprey (1968)
		12			13	0.01		Landscape and agricultural literature consensus	Duprey (1968)
		30		30-40% of total hydrocarbon	14-16	0.01	0.007	Municipal Refuse -- simulated test data	Gerstle and Kemnitz (1967)
		30		30-40% of total hydrocarbon	8-18	0.005	0.007	Landscape refuse -- simulated test date	Gerstle and Kemnitz (1967)
	250							Agricultural burning emission factor	Bay Area APCA (1969)
	252		30	36	24	35		Land clearing -- rework of Yocom (1956)	Feldstein, et al (1963)
		2-36	0.5-2.1	0.3-8.7				Simulated test data agricultural refuse	Darley (1966)
		4-19 (12.3 ave.)	0.4-3.3	1.0-5.6				Simulated test data -- grass and crop stubble	Boubel (1969)
		9-15 (10.6 ave.)						Field test data -- grass stubble	Boubel (1969)
		80			40	1-3		Domestic refuse -- estimated from literature	Hovey, et al (1966)
							14-15	Municipal refuse -- test data	Hangebrauck et al (1967)

detailed studies reported indicate that the contribution of partially oxygenated species to the total organic emissions can be quite significant, exceeding in some cases the 'total hydrocarbon' emission.

Much study remains to be done in order to arrive at more meaningful emission estimates from solid waste combustion. However, it is quite clear that alternatives to open burning and indiscriminate use of poorly designed and uncontrolled incinerators must be implemented.

2. Municipal Waste Breakdown

Introduction

In the development of estimates of emissions from solid waste combustion, detailed in Chapter III, Part C, a state-by-state breakdown of urban waste generation and disposal was made. This appendix presents the results and discussion of this breakdown.

Discussion

In the Systems Study of Air Pollution from Municipal Incinerators (PB 192378, A.D. Little, Inc., 1970) urban waste generation factors were presented for each state, based on an average generation rate of 5 lb/person day for household wastes plus a seasonally adjusted factor for yard wastes. Using the A.D. Little generation factors and population data from the U.S. Bureau of the Census, state estimates of total urban waste generation were compiled, as shown in Table I-3. By this procedure, the total urban waste generation for the United States is approximately 1.73 x 10^8 tons/year.

In order to estimate the amount of generated urban waste that is burned, some additional assumptions were made. That portion of the generated waste handled by municipal incineration was estimated from the assumption that municipal incinerators operate at fifty percent of listed capacity. State data on incinerator capacity were obtained from the A.D. Little report and from the National Emission Standards Study (Report to Congress of the Secretary of Health, Education and Welfare, March, 1970). Open burning was assumed to be the disposal mode for 25 percent of the total generated waste.

TABLE I-2

SELECTED EMISSION FACTORS FOR SOLID WASTE COMBUSTION SOURCES

Combustion Mode	Total Organic Emissions (lb/ton burned)
Incineration	
Municipal	4
Industrial and Commercial	14
Conical Burners (wood)	20
Domestic	40
Open Burning	
Municipal	45
Industrial and Commercial	30
Lumbering	30
Field and Crop	20
Land Clearance	40
Demolition and Construction	30
Coal Refuse	20
Forest Wildfires	40

Exceptions to the above assumptions were made where the questionnaire survey returns from the pollution control agencies provided data on the amounts of solid waste disposal by combustion, or where other data sources reported significant population areas having prohibitions on open burning.

The estimates summarized in Table I-3 thus present a crude approximation of the magnitude of the urban waste generation and disposal by combustion on a state-by-state basis.

TABLE I-3

STATE BREAKDOWN OF ESTIMATES OF WASTE GENERATION AND COMBUSTION

State	Waste Generation (lb/person day)	State Population (1,000)	Urban Fraction (%)	Urban Wastes (10^5 ton/ yr)		Waste Combustion (10^5 ton/ yr)
Alabama	6.4	3,373	60	23.638	A	--
					B	5.91
Arizona	6.5	1,752	91	18.911	A	--
					B	0.4*
Arkansas	6.2	1,886	49	10.451	A	--
					B	2.61
California	6.8	19,715	94	229.984	A	--
					B	57.50
Colorado	5.8	2,178	85	19.597	A	--
					B	4.90
Connecticut	6.0	2,988	87	28.465	A	9.00
					B	0.01*
Delaware	6.0	543	75	4.460	A	--
					B	1.12
Florida	6.8	6,671	86	71.197	A	8.05
					B	2.44*
Georgia	6.2	4,492	65	33.036	A	4.37*
					B	4.45*
Idaho	5.9	698	55	4.135	A	--
					B	6.16*
Illinois	6.0	10,978	86	103.379	A	6.02
					B	25.85
Indiana	6.0	5,143	65	36.606	A	1.33
					B	9.15
Iowa	5.9	2,790	55	16.524	A	--
					B	4.13
Kansas	6.0	2,222	65	15.815	A	0.06
					B	3.95

TABLE I-3 (continued)

State	Waste Generation (lb/person day)	State Population (1,000)	Urban Fraction (%)	Urban Wastes (10^5 ton/yr)		Waste Combustion (10^5 ton/yr)
Kentucky	6.1	3,161	48	16.892	A	2.10
					B	4.22
Louisiana	6.4	3,564	69	30.547	A	2.92
					B	7.63
Maine	5.8	977	60	6.205	A	--
					B	1.55
Maryland	6.2	3,875	83	36.391	A	3.93
					B	1.6*
Massachusetts	5.9	5,630	87	52.739	A	7.15
					B	13.18
Michigan	5.9	8,778	79	74.668	A	5.15
					B	18.67
Minnesota	5.8	3,768	67	26.722	A	0.42
					B	6.68
Mississippi	6.2	2,159	43	10.505	A	0.25
					B	2.63
Missouri	6.1	4,636	71	36.642	A	1.52
					B	9.16
Montana	5.7	682	55	3.902	A	--
					B	0.98
Nebraska	5.9	1,468	60	7.658	A	--
					B	1.91
Nevada	5.7	482	91	4.563	A	0.25
					B	1.14
New Hampshire	5.7	732	67	5.041	A	0.22
					B	1.26
New Jersey	6.0	7,085	97	75.070	A	2.25
					B	18.77
New Mexico	6.0	998	73	7.979	A	--
					B	2.00

TABLE I-3 (continued)

State	Waste Generation (lb/person day)	State Population (1,000)	Urban Fraction (%)	Urban Wastes (10^5 ton/ yr)		Waste Combustion (10^5 ton/ yr)
New York	6.2	17,980	91	185.135	A	31.65
					B	9.99*
North Carolina	6.2	4,962	45	25.265	A	--
					B	6.32
North Dakota	5.7	611	37	2.351	A	--
					B	0.59
Ohio	6.0	10,542	78	90.038	A	7.35
					B	22.51
Oklahoma	6.1	2,498	69	19.188	A	--
					B	4.80
Oregon	6.3	2,056	69	16.312	A	0.10
					B	0.25*
Pennsylvania	6.2	11,670	74	97.714	A	10.0
					B	30.0*
Rhode Island	6.0	922	89	8.986	A	1.35
					B	1.42*
South Carolina	6.2	2,523	45	12.848	A	--
					B	3.21
South Dakota	5.7	661	44	3.026	A	--
					B	0.76
Tennessee	6.2	3,839	57	24.758	A	--
					B	6.19
Texas	6.3	10,989	86	108.657	A	1.42
					B	27.17
Utah	6.0	1,061	86	9.994	A	0.52
					B	2.50
Vermont	5.7	438	40	1.825	A	--
					B	0.46
Virginia	6.3	4,686	69	37.175	A	2.64
					B	9.30

TABLE I-3 (continued)

State	Waste Generation (lb/person day)	State Population (1,000)	Urban Fraction (%)	Urban Wastes (10^5 ton/yr)		Waste Combustion (10^5 ton/yr)
Washington	6.4	3,353	72	28.204	A	0.52
					B	1.77
Wisconsin	5.9	4,367	69	32.445	A	13 *
					B	8.11
Wyoming	5.6	329	57	1.916	A	--
					B	0.48
Dist. of Columbia	6.2	746	100	8.442	A	2.8
					B	--
Totals		200,251		1,733,082		

A = Incineration, B = Open Burning, * = Data from questionnaire

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